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The report provides an evaluation of a new closed-breech, shoulder-fired weapon system proposed to DARPA by TAC-WEAP Ventures, Inc. It presents a recoil analysis that defines the boundaries for projectile weight and muzzle velocity. Specific projectile designs are developed and analyzed for interior ballistic and aerodynamic performance. Candidate fin- and spin-stabilized projectile designs are presented that incorporate a generic shaped-charge warhead, and a boost rocket motor is used to increase the range of the projectile. Vertical target dispersion analysis is presented using six-degree-of-freedom simulation on a 1500-foot engagement range.

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SYSTEM PLANNING CORPORATION

A Limited Performance Tradeoff Analysis of a Novel Closed-Breech, Shoulder-Fired Weapon System

DRAFT REPORT
SPC 1426

July 1992

Steven M. Buc

Prepared for

Land Systems Office
Defense Advanced Research Projects Agency

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1. BACKGROUND AND INTRODUCTION

TAC-WEAP Ventures, Inc. (TAC-WEAP), submitted an unsolicited proposal to the U.S. Army Missile Command for a unique closed-breech, shoulder-fired weapon system capable of safely launching heavy, large-caliber projectiles (greater than 90mm) at muzzle velocities greater than 100 fps that could be boosted by a small rocket motor to velocities capable of delivering the projectile to considerable ranges. The Land Systems Office (LSO), Defense Advanced Research Projects Agency (DARPA), reviewed the proposal and then contacted SPC, a DARPA LSO support contractor, to review and comment on the proposal package.

Following SPC review of the proposal, the potential payoff of the TAC-WEAP system was such that further SPC investigation was approved by DARPA under the existing support contract with SPC. SPC made a visit to TAC-WEAP to discuss the system, and a limited study was then undertaken to investigate the ballistic parameters of the proposed weapon system, identify the scientific nature of the TAC-WEAP claims, and project the capabilities and limitations of the system.

Photographs of the prototype system are shown in Figure 1. Without divulging any proprietary information about the proposed weapon system, the following summarizes its operation. To launch a heavy mass and large-diameter projectile safely from a closed-breech system such as that proposed by TAC-WEAP, a recoil mechanism is employed to mitigate the effects of recoil energy and momentum. The projectile, although relatively heavy, is also launched at a relatively low muzzle velocity to keep recoil parameters small. The launching mechanism operates on the principle of a high-low chamber pressure. A small amount of propellant is rapidly burned under high pressure, within a small space, and then vented into the launcher tube to propel the projectile out the muzzle under a controllable low pressure. The projectile is then boosted by an on-board rocket motor to achieve the desired range. TAC-WEAP has demonstrated the ability to safely launch projectiles of significant weight and diameter at muzzle velocities above 100 fps, which is an impressive achievement. They submitted the unsolicited proposed to obtain funding to demonstrate the second-stage rocket motor and to fully develop their prototype system.

The author wishes to acknowledge the invaluable assistance provided by Mr. David Vaklyes and Mr. George Sampson of System Planning Corporation and Mr. Manfred Schmidt of the Siemens Corporation, who participated on different occasions with the recoil experiments conducted in this study; and Mr. Hugh McElroy of Olin Ordnance, who provided advice and insights on the interior ballistic functioning of high-low pressure guns.

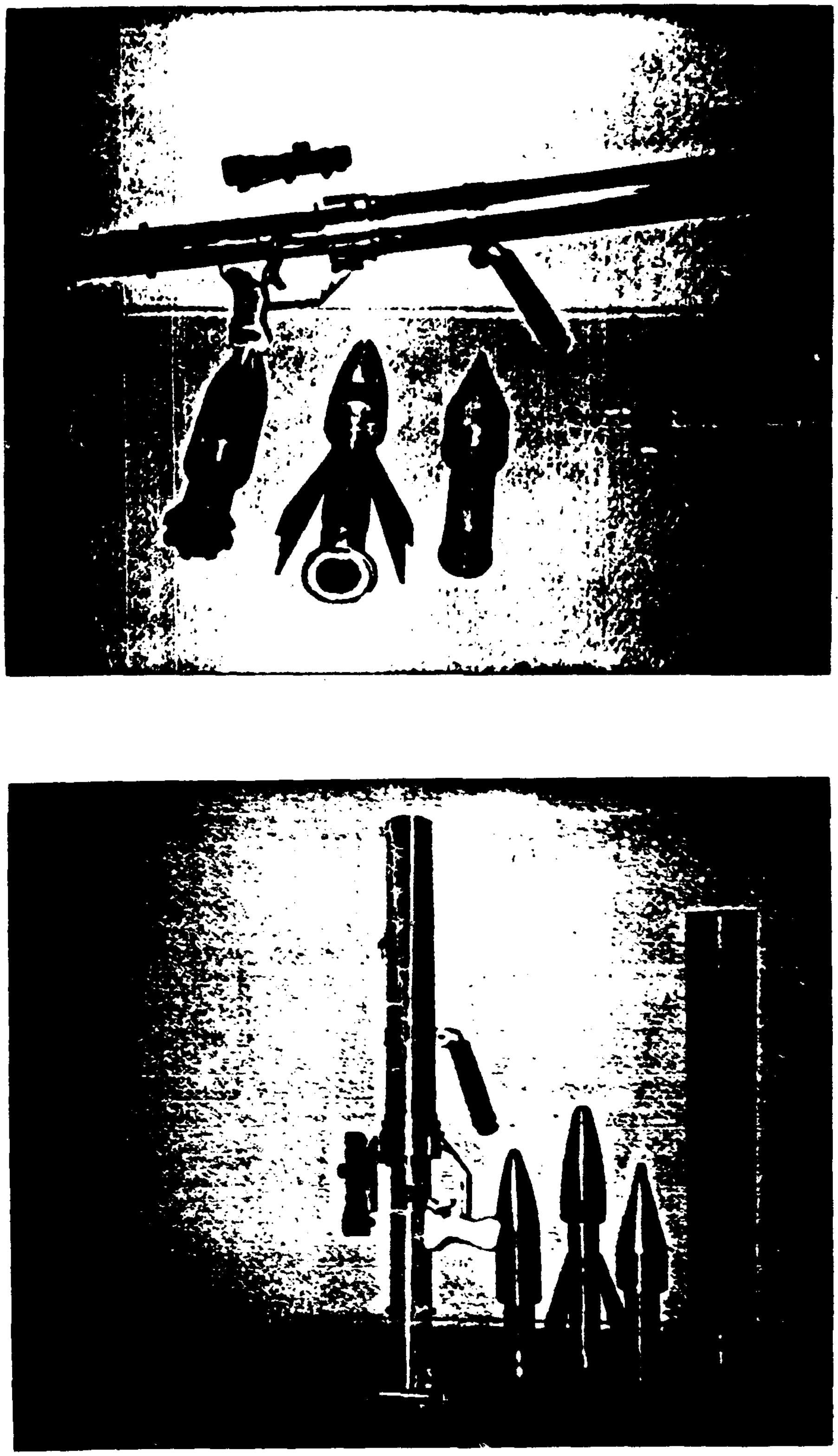

Figure 1. TAC–WEAP Prototype System

The advantages and disadvantages of present launcher systems are briefly described here to illustrate the advance in the state of the art that is offered by the TAC-WEAP system. Shoulder-fired recoilless weapons are presently used by the infantry soldier; these have large-caliber, highly lethal, explosive warheads and are basically adaptations of the old WWII bazooka. In the recoilless system, propellant gases are forced rearward out of a rocket nozzle in the back of the launcher to balance the recoil effects of a heavy projectile exiting the muzzle with significant velocity. A closed-breech system, on the other hand, does not allow propellant gases to exit to the rear to balance recoil effects. Whatever is supporting the launcher must absorb the recoil impulse and energy.

Each of these types of systems has unique advantages and disadvantages. The recoilless system allows heavy masses to be safely launched at high velocity. However, there is considerable back-blast to the rear that may kill or injure anyone in the way; even the gunner may be killed or injured if he fires within a closed structure such as a room or bunker. Other disadvantages of the recoilless system are loud noise and the launch signatures created upon venting of the back-blast that result in dirt and debris being thrown about. Some will also argue that supporting a weapon on the top of the shoulder is an unnatural and uncomfortable means of firing a weapon and induces gunner firing errors affecting accuracy.

A closed-breech system, on the other hand, has no back-blast, does not require the gunner to first examine who is to the rear, and allows the reduction or elimination of launch signatures. Unfortunately, since the gunner must absorb the recoil, the throw-weight (mass-velocity tradeoff) of such systems is severely limited.

The analysis presented in this study is based on information and experimentation acquired independently of the developmental work performed by TAC-WEAP and provides an objective evaluation of the proposed weapon system concept. This report begins with an in-depth assessment of the body of knowledge on recoil from shoulder-fired, closed-breech weapons and the implications on the performance of the proposed concept. Limited experimentation was also performed to expand this body of knowledge to include systems developing recoil energies and impulses greater than currently fielded shoulder-fired weapons.

Following this recoil analysis, which defines the boundaries for projectile weight and muzzle velocity, specific projectile designs are developed and analyzed for interior ballistic and aerodynamic performance. Consideration of the terminal effects of the projectile is made by incorporating a generic shaped-charge warhead. Candidate fin- and spin-stabilized projectiles are designed to incorporate this warhead, and a boost rocket motor is used to increase the range of the projectile. Limited interior ballistic analysis of the launcher and rocket motor and structural analysis of the projectile are presented to evaluate the required

weight of projectile body components. Finally, 6-degree-of-freedom trajectory analysis is used to assess the range, accuracy, and dispersion characteristics of the generic projectile designs against a point target. The performance tradeoff analysis that is presented takes into consideration all of these weapon system aspects.

The analysis is limited in that the projectile designs and launcher parameters were not iterated, based on analysis results, to an optimized design. Performing weapon system design and analysis is very much like riding a merry-go-round—it doesn't really matter at which point you get on, but you have to go around a few times before you get a feel for the whole picture. In ballistics, the analyst must begin with an idea of the system being developed, then iterate system parameters through interior ballistics, structural dynamics, aerodynamics, and terminal ballistics, and then reiterate the process until the design converges on an optimal solution. In this study, a preliminary analysis was first made through all the phases of design in order to determine the magnitude of the launcher and projectile performance parameters involved. Then one final detailed analysis was made, the results of which constitute the body of this report. The designs presented here, therefore, are not optimal, but are perhaps close enough to assess the performance advantages, limitations, risks, and payoffs of the proposed TAC-WEAP weapon system.

2. ANALYSIS OF SYSTEM RECOIL

This chapter describes the SPC analysis conducted to ascertain the credibility of the recoil claims of TAC-WEAP for the closed-breech, shoulder-fired weapon system. It also presents a description and analysis of a recoil test designed by the author to quantify recoil parameters in which he used himself as the test subject.

A. ANALYSIS OF THE STATE OF THE ART

A fundamental consideration when evaluating the feasibility and utility of a shoulder-fired weapon system is to assess the effects of system recoil on the gunner and the impact of maintaining safe recoil levels on the range, accuracy, and lethality of the munition. Over the last forty years, rifle recoil has received serious attention of the military and sporting community only during periods when new rifles and weapons were being introduced or evaluated for procurement. A definitive scientific assessment has not been made, however, on what constitutes safe recoil levels for riflemen. The most comprehensive literature review on this subject was prepared in 1982 by Mr. Robert Spine of the U.S. Army Human Engineering Laboratory; his report is presented in the appendix to this report. In 1987, he stated that little progress had been made in answering some of the most fundamental issues and that no standard for maximum recoil levels had been established.[1]

The fundamental problem in establishing a maximum safe recoil level for a shoulder-fired weapon is that recoil effects on a gunner are very subjective. The physical recoil of the weapon, or what can be called the Newtonian recoil, is only one aspect of the "perceived recoil" on the gunner. The Newtonian recoil is processed through several components of the weapon (i.e., recoil buffer, stock, and pad) prior to passing through the gunner's clothing to his shoulder to be perceived as a kick or in some cases to cause pain or a bruise. A logical objective in establishing limits on weapon recoil, therefore, is to avoid injuring the gunner, knocking him off his feet, or making him hesitant to use the weapon. The occurrence of any one of these three negative effects of recoil will make the weapon less than fully effective from an accuracy and lethality perspective and should, therefore, be avoided. Unfortunately, it is much easier to measure scientifically the parameters of Newtonian recoil than those of perceived recoil; for this reason, the body of knowledge is incomplete. The recoil analysis presented here will, therefore, build upon our understanding of Newtonian recoil and the

[1]Telecon with author.

subjective nature of perceived recoil as reported by other authors and as experienced by this author in an attempt to establish scientific parameters. If perceived recoil can be quantified, perhaps we will be less constrained by the parameters of Newtonian recoil when evaluating the recoil safety of unique weapon designs such as the TAC-WEAP system evaluated here.

Newtonian recoil arises from Newton's third law of motion: to every action there is an equal and opposite reaction. In the case of a closed-breech launcher, the forces expelling the projectile from the barrel are also forcing the launcher in the opposite direction. Due to the law of conservation of momentum, the summation of these accelerating forces, acting over the finite time that the projectile is in the barrel, results in the projectile and some of the propelling gases having the same momentum forward as the launcher has rearward. The total energy expended during the interior ballistic event is also conserved. However, conservation of energy has no relation to the direction or form in which the energy dissipates, so the projectile and recoiling launcher will most likely not have the same kinetic energies. These kinetic energies must, therefore, be calculated based on the momentum of the system; they are also very important in assessing Newtonian recoil.

Newtonian recoil parameters may be calculated using the hypothetical case presented below. The M203 40mm grenade launcher is a shoulder-fired weapon, integrally attached below the barrel of the M16 rifle and M16 variants. The entire launcher, including M16 rifle, weighs approximately 12.1 pounds. The 40mm projectile weighs about 0.375 pound and has a muzzle velocity of about 240 fps. In this example, the weight of the propelling charge is not factored in since it is very small compared to the weight of the projectile, and a precise interior ballistic analysis is required to determine the forward momentum of the gases.

The momentum of the projectile is:

$$\frac{0.375 \ x \ 240}{g} = 2.8 \ lb\text{-}sec \tag{1}$$

where g = 32.2 fps (gravity).

Since momentum is conserved, the recoiling velocity of the launcher may be calculated as follows:

$$\frac{2.8 \ x \ g}{12.1} = 7.5 \ fps. \tag{2}$$

The recoil energy is:

$$7.5^2 \cdot \frac{0.5 \times 12.1}{g \cancel{\times 7.5}} = 10.6\ ft\text{-}lb. \tag{3}$$

For curiosity, the energy of the projectile is:

$$240^2 \cdot \frac{0.5 \times 0.375}{g \cancel{\times 240}} = 335.4\ ft\text{-}lb. \tag{4}$$

This is considerably more energy than that generated in the recoiling launcher, which is good, since it ensures that the projectile flies to the target rather than the launcher flying backward at other soldiers.

Nevertheless, I have calculated that the M203 generates Newtonian recoil parameters of 7.5-fps velocity, 2.8 lb-sec momentum, and 10.6 ft-lb kinetic energy. Is this too much, just right, or not enough? Unfortunately, we are not sure, since these parameters do not tell us how the body reacts. The accepted practice has been to compare candidate recoil energy and momentum to existing systems and see how things measure up to the subjective evaluations of those who have fired those systems. Figure 2, taken from Spine's report, gives such a comparison. Table 1 shows the parameters for additional systems as I have calculated them.

Figure 2 and Table 1 are organized in roughly increasing recoil magnitude in terms of recoil velocity, recoil energy, and recoil momentum. These data are also organized to reflect increasing magnitude of perceived recoil, as observed by the author and reported by Spine. The key Newtonian parameters, therefore, that track directly with an increase in perceived recoil appear to be free recoil velocity and free recoil energy. This observation agrees with comments provided to me by Dr. Robert L. McCoy of the Ballistics Research Laboratory (BRL).[2] He commented that establishing a recoil standard based on recoil momentum was not the right parameter, that free recoil energy and velocity were, in his opinion, the key items affecting perceived recoil levels. Dr. McCoy also commented that a cross-section of good military riflemen had reached a consensus that 30 ft-lb of energy was a comfortable limit and that the ideal upper limit for safety was less than or equal to 75 ft-lb. Spine, on the other hand, indicated that the Human Factors Laboratory (HEL) typically recommends a 3.0 lb-sec impulse limit on recoil. The unfortunate aspect to this continuing informal debate about recoil energy and momentum is that both opinions are equally valid, depending

[2]Telecon, 1987.

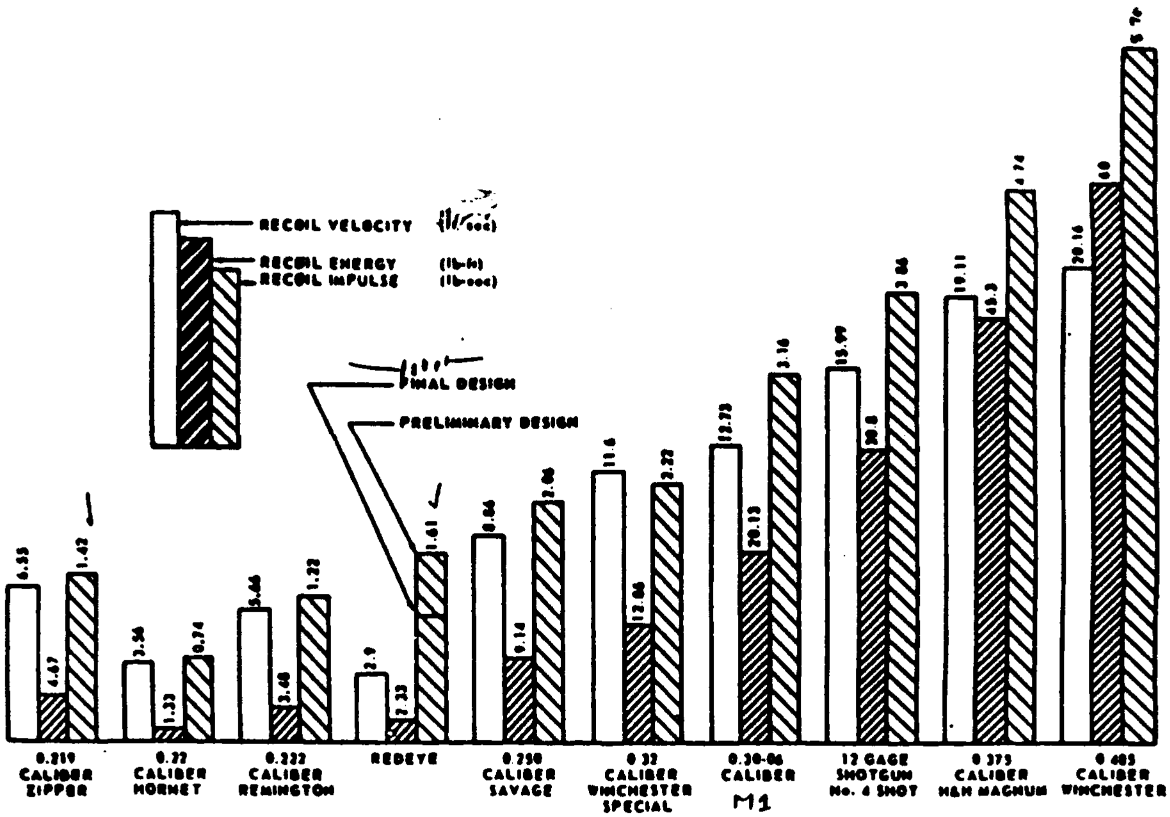

Figure 2. Recoil Parameters of Various Weapons

on which service is writing the safety requirements for the system in question. The following excerpt from a 1990 Marine Corps Required Operational Capability (ROC) for a muzzle-launched ordnance system (or rifle grenade) highlights how difficult it is for the services to resolve their recoil safety issues.

> It is desired that the recoil effect when launching the projectile will be no greater than normally experienced by a combat equipped Marine when firing the M203 grenade launcher. In any case, the recoil shall not be so great as to cause degradation in man-fired accuracy or a reluctance to fire subsequent rounds. A combat equipped rifleman shall be able to fire the basic load in a 45 second time period, followed by a four hour period for resupply, when he will again be able to repeat the firing of a basic load, all with no significant physiological effects.

This requirement is an attempt to have the system in question meet both the recoil momentum and recoil energy safety limits without considering whether or not they are conflicting. The result is a conflicting safety requirement. To use the term "recoil effect" in the requirement and not explicitly state recoil momentum or energy has the effect of implicitly stating that it is the level of perceived recoil which is of concern. We, as yet, do not have a criterion for perceived recoil, so we must subjectively evaluate the meaning of

Table 1. Recoil Parameters for Selected Shoulder-Fired Systems

System	Projectile Weight (g)	Projectile Velocity (fps)	Projectile Momentum = Recoil Momentum (lb-sec)	Launcher Weight (lb)	Free Recoil Velocity (fps)	Free Recoil Energy (ft-lb)
M-16A1 w/20-round magazine	3.56	3281	0.8	7.2	3.6	1.45
7.62mm FN FAL rifle	9.3	2756	1.8	9.5	5.95	5.22
M203 Grenade Launcher	170	240	2.8	12.1	7.5	10.6
0.50-Caliber Sniper Rifle	42.9	2913	8.56	34	8.1	35 (with muzzle break 22.4 ft-lb)
MECAR 37mm Rifle Grenade on FN FAL	295	253	5.11	9.5	17.3	44.3
MECAR 55mm Grenade on FN FAL	790	105	5.68	9.5	19.3	55
IMI MA/AP 65mm Grenade on Galil rifle	600	167	6.86	9.6	23	79
IMI MA/AP 65mm Grenade on M-16A1	600	148	6.0	7.2	27	82

the Newtonian parameters on this "recoil effect." The M203 has a recoil momentum, as shown in Table 1, of 2.8 lb-sec and a free recoil energy of 10.6 ft-lb. One may notice that 2.8 lb-sec is below the HEL-recommended limit of 3.0 lb-sec, and that 10.6 ft-lb energy is well below the 30 ft-lb BRL consensus. The M203 should, therefore, pass the subjective safety test under both criteria. In fact, it does, magnificently. I have personally fired the M203 basic load within a 45-second time period and went on to fire five basic loads within 1 hour with absolutely no discomfort or injury, however minor. My accuracy actually improved with each subsequent shot. I was also not fully combat equipped, which means that

I was wearing only a fatigue shirt and no flack vest or nylon web gear, so the butt of the rifle was directly against my shoulder.

There is no doubt, therefore, that if the candidate system responding to this ROC satisfies the first sentence of this paragraph, it will satisfy the remaining two requirements. So why are these extra requirements stated? They can only be there to allow the Marines to violate the first requirement—that perceived recoil levels remain at or below that of the M203. In fact, some of the candidate systems responding to this ROC are items 5 through 8 in Table 1; these four rifle grenade systems are not nearly as comfortable to fire as the M203, but the author of this ROC realized that if greater firepower than the M203 is required, a more definitive understanding of perceived recoil must follow, whether they can quantify these recoil safety limits or not.

Spine provides some interesting qualitative data on the effects of recoil energy on shoulder tissue damage. Reviewing these data may help focus subsequent quantitative analysis techniques. Spine reports that a study using the M1 rifle was conducted in 1955 in which "the ammunition was varied to produce differing recoil (energies). The result . . . showed that marksmanship performance was constant when recoil was varied from 11.0 to 19.3 ft-lb," but as it increased up to 25.5 ft-lb, "significant differences in all measures of marksmanship performance were noted." This is not very specific, but clearly something was bothering the gunners when the energy exceeded 19.3 ft-lb. Spine goes on to explain that seven of the gunners experienced some redness and swelling during the experiment and that fifteen received bruises:

> More subjects in the two higher recoil groups (25.5 and 19.3 ft-lbs) developed bruise areas compared to the two lower recoil groups (14.9 and 11.0 ft-lbs).

I can attest to that. While firing the M1 rifle wearing simply a shirt, I realized painful bruising after firing only six rounds, and could not get myself to pull the trigger again, at least not while the rifle was at my shoulder. However, after a break of several minutes, I switched hands and fired from my left shoulder, but only after placing a 0.75-inch-thick paperback book under my shirt, between my shoulder and the rifle butt. That paperback book made all the difference. I went on to fire several more eight-round clips accurately with no discomfort. The same condition is true for me with a 12-gage shotgun. I can fire about four rounds from my shoulder before it hurts too much, but with a flack vest or using a paperback book to cushion my shoulder, I can fire all day long.

The Marines have realized this phenomenon when protecting the shoulder from the rifle butt, and that is why the ROC is written with these conflicting requirements. However, there are no quantitative criteria against which to design a shoulder-fired weapon to meet the perceived safe recoil limits for a soldier wearing combat equipment, such as a flack vest,

which can make a tremendous difference in the level of perceived recoil. Figure 1 showed the Newtonian parameters for the M1 rifle and 12-gage shotgun. Both exceed the suggested momentum limit of 3.0 lb-sec. Both are also within the suggested comfortable energy limit of 30 ft-lb. Depending on what I am wearing, I have found both of these weapons to be either very uncomfortable or very comfortable to fire.

This paradox, as it stands, makes it nearly impossible to assess the potential recoil effects of a shoulder-fired weapon prior to its actual fabrication and testing. Unfortunately, once a candidate system is fabricated and tested, it represents only one point design in a family of tradeoffs for that weapon system. Since the projectile momentum and launcher weight drive the Newtonian recoil parameters of recoil velocity, energy, and momentum—which in turn drive the perceived recoil—one should logically first establish a limiting projectile momentum and launcher weight boundary to design to. Currently, this type of systematic approach to weapon design is not available, because quantitative parameters for perceived recoil do not yet exist for systems that are outside established norms.

To effectively perform a system tradeoff analysis, it is necessary to develop quantitative data. From the weapon system design point of view, the first recoil parameter that must be established is recoil momentum. The recoil momentum is equal to the momentum of the projectile leaving the launcher and, therefore, establishes the projectile mass and velocity tradeoff. It is also independent of the weight of the launcher and recoil buffer systems, which will reduce the perceived recoil on the gunner. For this reason, the Newtonian recoil momentum is a firm design parameter of the weapon system. Once a limiting recoil momentum is established, the projectile designer can begin to trade off critical system parameters such as the projectile diameter and weight, warhead lethality, launch velocity, and second-stage rocket motor, if required.

Given that the momentum of the projectile is transferred to the launcher, which in turn transfers its momentum to the gunner, a logical limiting momentum might be that which causes the gunner to lose balance. An experiment could be devised to quantify this requirement. A recommended test approach would be to select a representative cross-section of service personnel and subject them to recoil momentum tests to determine their threshold momentum for losing balance. Other particulars of the test might include developing a suitable mechanism for generating and measuring recoil momentum, as well as other Newtonian recoil parameters, and choosing appropriate firing positions for the gunners.

B. RECOIL TESTING AND ANALYSIS OF RESULTS

I devised a system recoil test to determine the threshold momentum for losing balance and used myself as a test subject. This test is fully reproducible, and others may find the data useful. The test setup involved suspending a 23.44-lb spare tire horizontally at the end

of a long rope, similar to a pendulum. The rope was suspended from an I-beam approximately 20 feet off the floor. If the tire was pulled back and displaced a known vertical distance, then released to swing freely, it would develop a known velocity as it reached the bottom of its swing, according to the following relationship:

$$V = (2gh)^{0.5}, \tag{5}$$

where V = velocity in fps, g = gravity (32.2 fps^2), and h = vertical displacement in feet.

This formula results from equating the potential energy of the tire at its displaced height to its kinetic energy at the bottom of the swing. Since the energy of the system must be conserved, the potential energy when the system is at rest equals the kinetic energy when full velocity is realized and there remains no potential energy. This is a safe assumption as long as displacements, velocities, and friction losses remain small.

I used a rifle simulant, to transfer the momentum and energy of the tire to my shoulder when it was at the bottom of its swing. The rifle simulant was a 36-inch 2x3 (nominal) with an 0.5-inch-thick plywood butt with a vertical height of 4.25 inches and horizontal width of 1.5 inches, nailed into the end of the 2x3. This wooden assembly weighed 2.44 pounds.

To avoid injury to my shoulder during the experiment, I wore an 8.63-lb model 1952A armor vest. Including the vest and my clothing, my weight was 151 pounds, and my height is 5 feet 10.5 inches. I gripped the rifle simulant firmly with both hands, the left hand approximately 13 inches forward of the right, approximately 9 inches from the butt. While pushing the rifle simulant firmly on the vest against my right shoulder, I assumed two different firing positions: a comfortable standing firing position, and a comfortable kneeling firing position with the back of my left elbow resting on the forward portion of my left knee.

The rope was adjusted so that the tread of the tire would impact the muzzle of the barrel squarely. A horizontal wire was attached to the tire in order to make consistent and accurate height readings. Then an assistant swung the tire back to a known displaced vertical height, as measured by a staff which he held, then released the tire, which swung down and impacted the barrel. After each test, I paused to reflect on the experience and make notes. Then I resumed my firing position and continued the test sequence. At least two tests were performed for each firing position and each tire displacement.

The velocity of the tire was calculated for each height based on equation (5). The momentum of the tire at this velocity is considered the recoil momentum of the system. The free recoil velocity was determined by assuming an inelastic collision of the tire and the rifle simulant, where the recoiling mass became the total mass of tire and rifle (25.88 lb). This convention was chosen since it appeared that the tire continued to travel forward with the

rifle and only stopped after my body completely recoiled. Free recoil energy was calculated using the free recoil velocity and the total mass of tire and rifle simulant. The Newtonian recoil parameters for the test series are given in Table 2.

Table 2. Newtonian Recoil Parameters for Recoil Test

Tire Height (ft)	Tire Velocity (fps) wt = 23.44 lb	Recoil Momentum (lb-sec)	Recoil Velocity (fps) wt = 25.88 lb	Recoil Energy (ft-lb)
0.5	5.67	4.13	5.14	10.6
1.0	8.00	5.82	7.25	21.1
1.5	9.83	7.16	8.90	31.8
2.0	11.40	8.26	10.30	42.5

The recoil results shown in Table 2 seemed satisfactory for simulating a range of weapon systems, such as those in Table 1. In terms of recoil momentum, all these values are for systems more stressful than the M203 grenade launcher. Recoil energies and velocities are nearly at rifle grenade levels and cover all the lower energy systems as well. The testing stopped, however, at a tire height of 2 feet because of my subjective recoil evaluation.

Subjectively, the 6-inch tire height presented no perceived recoil problems from either the kneeling or standing position, and I would classify this as a comfortable recoil. At the 1-foot height, the shock to my body was perceptibly greater, but there appeared to be no side effects from the experience, and although it was not the most comfortable jolt, I could tolerate repeated shots without complaint. At 1.5 feet, my head rattled, my eyes crossed, and a dull headache began. Additionally, I noticed that I wanted to take a step back when standing, or drop my left hand to the ground when kneeling to maintain my balance during the recoil. However, if I concentrated on maintaining my balance, I could do so without moving. At 2 feet, the jolt was considerable. I definitely received a headache from the experience, and even if concentrating I would have to take a small step back when standing or drop my left hand to the ground for balance when kneeling. My headache passed within a half-hour of the testing, and I did not receive even the slightest shoulder injury as a result of wearing the armor vest.

In analyzing these test results, one must consider that my body was being subjected to unmitigated recoil. Other than wearing the armor vest to prevent localized shoulder injury, there were no buffers or recoil mechanisms to reduce the recoil velocity of the rifle and the instantaneous recoil shock to my body. Of course, this is also the case for the majority of

shoulder-fired weapons, including those in Table 1 and Figure 2, except the 0.50-caliber sniper rifle, which incorporates a recoil mechanism. All of the rifle grenades listed in Table 1 operate by placing the grenade over the end of the rifle muzzle. Therefore, the rifle is no different than the simulated rifle in my experiment. All of the recoil is transmitted through a very stiff medium directly to the shoulder. Under these circumstances, the safe recoil limit for me is perhaps item 5 in Table 1, the MECAR 37mm rifle grenade fired from the 7.62mm caliber FN FAL rifle.

In my discussions with Robert McCoy, however, he also mentioned that perceived recoil (pain) "is drastically altered by the shape and duration of the force-time curve," and that "buffers mitigate recoil force." Whereas in my experiment, I successfully eliminated all localized recoil pain in my shoulder by wearing the armor vest, my head continued to experience considerable pain in terms of rattling and a headache. Therefore, the instantaneous recoil forces were still in excess of what my body, as a whole, could safely tolerate. Unfortunately, none of the Newtonian recoil parameters of momentum (impulse), velocity, or energy is specific enough to identify the instantaneous force against my shoulder. Momentum is the closest, but it only describes the total force times time that passes into my body. This impulse may take any shape, some more comfortable than others.

Since my shoulder and body are not calibrated to give force-time output, I modified my rifle simulant with a spring-loaded recoil mechanism and repeated the previous recoil tests. This mechanism consisted of a 24-inch long, 3/8-inch-diameter threaded rod, supported between two eyebolts. A 15-inch compression spring composed of four in-series springs and washers was placed over the rod, between the eyebolts, and adjusted with locking nuts to place approximately 7 inches of rod forward of the end of the rifle. Figure 3 shows a schematic of the recoil mechanism attached to the wood rifle simulant.

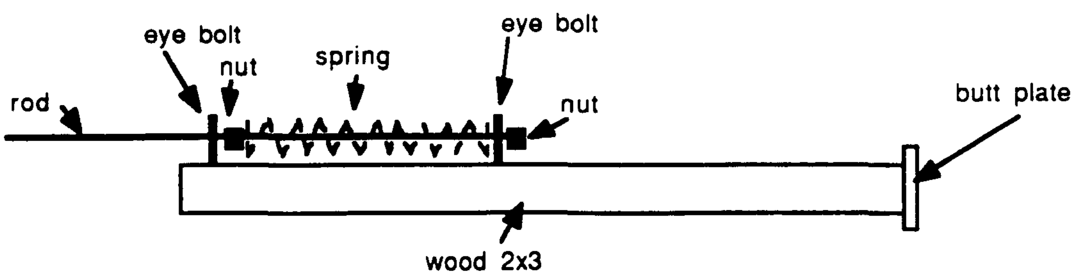

Figure 3. Rifle Simulant With Spring-Loaded Recoil Mechanism

The spring stiffness, (3.35 lb/in) was determined by placing a known weight on the end of the rod while the rifle was supported upright. The experiment was then performed as before, but this time without the use of the armor vest and with dramatically different results.

The spring was initially adjusted so that it had no precompression. At the 6-inch tire height, when the tire impacted the end of the rod, the rod recoiled about 5 inches, and then pushed the tire slightly back. My body recoiled negligibly and there was effectively no perceived recoil. It was like the tire did not hit the rifle. At the 1-foot tire height, the recoil mechanism bottomed out at 6.75 inches when the tire hit the forward eyebolt. Again, however, there was negligible perceived recoil. The spring was then adjusted to give a 4.25-inch precompression. This way it would initially have a resisting force and not bottom out during recoil. The 1-foot height was repeated. The recoil mechanism held at about 5 inches and the perceived recoil was extremely soft. At 1.5 feet, the tire just about bottomed out the recoil mechanism with 6.75 inches of recoil. Perceived recoil was again very comfortable. The tire was then raised to 2 feet and released. The recoil mechanism bottomed out and a slight jolt was felt when this happened. However, the recoil was still comfortable, even without the armor vest, and I did not lose balance. Unfortunately, even though the recoil mechanism was bottoming out, the spring could not be precompressed any further because the rear eyebolt was beginning to bend back under the force. Nevertheless, the test was then performed at a tire height of 2.5 feet. This seemed like an incredible undertaking considering the recoil effects experienced at 2 feet without the recoil mechanism. At 2.5 feet, the recoil mechanism again bottomed out at 6.75 inches of recoil, and a slightly greater jolt was felt when this happened. The perceived recoil, however, was still comfortable, but I was forced to take a small step backwards under the impulse. The test was then stopped at this recoil level because the recoil mechanism was at its mechanical limit.

The Newtonian recoil parameters for this series of testing are presented in Table 3. Since the addition of the recoil rod and spring changed the mass of the recoiling parts, some values change slightly. The rod weighed 0.75 pound, and only this weight is added to the weight of the tire, since these are forward of the recoil spring and therefore represent the recoiling mass (24.2 pounds).

The maximum recoil force in the spring, which is also the maximum force transmitted to the shoulder can be estimated from the recoil stroke. The recoil energy absorbed by the spring can also be estimated from these results. This is simply the area under the force-distance curve for the spring setting and recoil stroke (assumed linear). Table 4 presents this information.

Table 3. Newtonian Recoil Parameters for Recoil Test Using Spring-Loaded Recoil Mechanism

Tire Height (ft)	Tire Velocity (fps) wt = 23.44 lb	Recoil Momentum (lb-sec)	Recoil Velocity (fps) wt = 24.2 lb	Recoil Energy (ft-lb)
0.5	5.67	4.13	5.5	11.4
1.0	8.00	5.82	7.74	22.5
1.5	9.83	7.16	9.53	34.1
2.0	11.4	8.26	11.0	45.4
2.5	12.7	9.24	12.3	56.9

Table 4. Recoil Force and Energy in Recoil Spring Spring Constant of 3.35 lb/in

Tire Height (ft)	Start Force (lb)	Recoil Length (in)	Stop Force (lb)	Spring Energy (ft-lb)
0.5	0.0	5.00 (est.)	16.8	3.5
1.0	14.2	5.00 (est.)	31.0	9.4
1.5	14.2	6.75	36.9	14.4
2.0	14.2	8.2 (est.)	41.7 (est.)	19.0 (est.)
2.5	14.2	9.5 (est.)	46.0 (est.)	24.0 (est.)

The more accurate results are for the 1.5-foot swing height, since the recoil stroke was effectively the available recoil length. The first two results are rough observations, and the last two bottomed out on the eyebolt and are estimates of what the settings would have had to be to have smooth recoil based on the 1.5-foot test. In hindsight it may have been useful to have attached a recording device to the rod to mark its recoil stroke along the rifle more accurately. Such a device was used in subsequent testing. Of particular interest, however, is that the energy absorbed by the spring in the 1.5-foot test is only about 42 percent of the energy in the recoiling mass as compared with the results presented in Table 3. This makes more sense when one considers that the rifle was not fixed in space during the event, but was recoiling along with the shoulder and body. The end of the rod, therefore, was in contact with the tire over a longer distance than the recoil stroke would imply. Another

useful experiment would be to test this hypothesis by fixing the rifle in a rigid mount and then observing the rod recoil; it should be longer.

Recapping the recoil experiments performed thus far, we see that the addition of a simple spring-loaded recoil buffer dramatically reduces the perceived recoil on the body. A relatively elastic recoil buffer eliminates the need for direct shoulder protection such as the padding provided by an armor vest, as well as eliminating the intense general shock to the body caused by the rapid transferring of the kinetic energy in the recoiling mass to the body. The end result is that the perceived recoil threshold at which no pain was experienced for the Newtonian parameters of recoil momentum, recoil velocity, and recoil energy increased from 5.82 lb-sec to 9.24, 7.25 fps to 12.3, and 21.1 ft-lb to 56.9, respectively, comparing the 1-foot swing height to the 2.5-foot swing height with and without the recoil buffer. In addition, by using a calibrated spring in the recoil buffer, I was able to estimate that my shoulder and body can comfortably tolerate, without padding protection, an instantaneous recoil force of at least about 46 pounds spread over the 6.4-in^2 area of the simulated butt plate. This is only an approximate limit, since the recoil mechanism bottomed out and higher recoil forces could not be simulated. Depending on the measurement accuracy of this force and pressure limit and its applicability to a cross-section of body sizes and builds, this force becomes a fundamental recoil parameter to use in designing shoulder-fired weapon systems. In other words, rather than state recoil requirements in terms of impulse (momentum) or energy with all their caveats, one can simply establish an instantaneous recoil force and pressure limit on the shoulder, and work the design backwards from that point. Further research may show that these criteria may need to incorporate a time parameter over which this recoil force and pressure acts on the shoulder, as well as adjustments for body sizes, since the body is an integral part of the recoil mechanism. Nevertheless, the new recoil data will provide both a quantified Newtonian recoil parameter and a quantified perceived recoil parameter.

Although the new recoil criterion uses terms of force and time, it should not be confused with what has traditionally been called the "recoil impulse" or "momentum." This new criterion is certainly an impulse, since it is described by force and time, however, it is an impulse that is arrived at by considering the interaction of the recoiling mass, recoil buffer, and recoiling body. All three of these components affect the form of the perceived recoil impulse described here. The impulse or momentum of the projectile and recoiling mass is only indirectly related to this perceived force or impulse parameter.

Proceeding on the hypothesis that the source of perceived recoil, or pain, is the force transmitted to the shoulder and its dispersal through the body, finding an upper limit for this force while wearing an armor vest is a logical extension of the experiments performed thus far. If 46 pounds is a first approximation of the force limit for an unprotected shoulder, a candidate projectile being launched from a weapon using the recoil system described here

is limited to about 9.24 lb-sec using the 2.5-foot tire height data in Table 3. If an armor vest was now incorporated for shoulder protection or even a simple padded butt plate, a higher recoil threshold may be achieved. This limit would then establish an upper limit for reasonable projectile launch momentum.

To test this, the recoil buffer was modified to give greater stiffness and, therefore, greater recoil forces on the shoulder. Three additional heavy-duty eyebolts were placed between each of the four in-series compression springs to now make them act in parallel. The result was a spring constant of 40 lb/in with a maximum recoil travel of about 2.75 inches. Therefore, when the springs bottomed out, the recoil force would reach a level of about 110 pounds. In addition, for these tests, two felt-tip pens were secured to the back of the rod, between two washers and hex nuts, and forced against a strip of masking tape attached to the upper side of the wood barrel. This mechanism would now allow accurate recording of the recoil travel during each test. Different levels of precompression of the springs were tried in the assembly, so the starting force for all tests was calculated as indicated.

Table 5 shows the recoil force and spring recoil energies for the tire heights tested. Table 6 shows the Newtonian recoil parameters for this test series. Using the vest and recoil mechanism, I was able to withstand the recoil from tire heights up to 5 feet. Once the recoil springs bottomed out (3 feet and higher), the residual recoil velocity would give a significantly greater jolt, as if there was no recoil mechanism present, so my perceived recoil would naturally increase. As a result, my perceived recoil at the 5-foot level began to match the 1-foot level as tested without the spring buffer (Table 3). Additionally, only at the 5-foot level did I have to take a small step backward to maintain balance. Nevertheless, with the aid of the armor vest, the recoil effects were still comfortable.

To further increase the Newtonian recoil parameters, two tires were used in the next test series. The combined tire weight was 47 pounds. Table 7 shows the recoil parameters for the tire heights tested. Since all tire heights bottomed out the recoil spring, no new force levels could be determined. The 2-foot swing height still produced a comfortable perceived recoil level. However, with the 3-foot height, I was pushed off balance and could not regain balance, even when concentrating on doing so. This, of course, could be an effect of insufficient recoil travel in the springs. The trend in the testing is that progressively higher levels of recoil can be comfortably tolerated and balance maintained as recoil travel and spring force increases. In addition, the testing has shown that the padded shoulder can tolerate at least 110 pounds of force spread over this size butt plate.

Table 5. Recoil Force and Energy in Recoil Spring (Spring Constant at 40 lb/in) First Test Series

Tire Height (ft)	Start Force (lb)	Recoil Length (in)	Stop Force (lb)	Spring Energy (ft-lb)
1.0	13.8	1.89	89.4	8.13
1.5	13.8	1.96	92.2	8.66
1.0	40.0	1.38	95.1	7.77
1.5	40.0	1.50	99.8	8.74
2.0	40.0	1.58	103.0	9.41
2.5	40.0	1.70	108.0	10.50
3.0	40.0	bottomed out @ 1.75	110.0+	10.9+
3.5	40.0	bottomed out @ 1.75	110.0+	10.9+
4.0	40.0	bottomed out @ 1.75	110.0+	10.9+
5.0	40.0	bottomed out @ 1.75	110.0+	10.9+

Table 6. Newtonian Recoil Parameters for Recoil Test Using Spring-Loaded Recoil Mechanism (k=40 lb/in)

Tire Height (ft)	Tire Velocity (fps) wt = 23.44 lb	Recoil Momentum (lb-sec)	Recoil Velocity (fps) wt = 27.00 lb	Recoil Energy (ft-lb)
0.5	5.67	4.13	4.93	10.2
1.0	8.00	5.82	7.59	24.2
1.5	9.83	7.16	8.54	30.6
2.0	11.4	8.26	9.85	40.7
2.5	12.7	9.24	11.0	50.8
3.0	13.9	10.1	12.0	60.9
3.5	15.0	10.9	13.0	70.8
4.0	16.1	11.7	14.0	81.9
5.0	17.9	13.0	15.5	101.0

**Table 7. Newtonian Recoil Parameters for Recoil Test
Using Spring-Loaded Recoil Mechanism
(k=40 lb/in with two tires)**

Tire Height (ft)	Tire Velocity (fps) wt = 47.0 lb	Recoil Momentum (lb-sec)	Recoil Velocity (fps) wt = 50.6 lb	Recoil Energy (ft-lb)
1.0	8.0	11.7	7.45	43.6
2.0	11.4	16.6	10.6	88.0
3.0	13.9	20.3	12.9	131.0

Note: All tests bottomed out the recoil spring. See Table 5 for forces and energies at bottom-out condition.

Since the modifications made to the recoil spring stiffness allowed greater forces to be generated prior to bottoming out, we then retested the recoil limit on the unprotected shoulder to see if we could revise the 46-pound limit estimated from the previous testing. Using the parameters in Table 5, the tire was swung at 6-inch, 1-foot, and 1.5-foot heights. The 1.5-foot height was my limit for using the bare wooden butt plate and recoil spring. There was no visible bruising to my shoulder, but I felt that at any higher recoil levels it would begin. At this force level, about 100 pounds, unpadded recoil using the recoil buffer was still comfortable.

In summary, the recoil testing was considered complete at this point in the study. Although it appears that higher recoil levels may be supported by an average person, the limitations of the test equipment employed did not allow a full range of experimentation. Nevertheless, this testing has presented a preponderance of evidence against the current *ad hoc* limitations on recoil from shoulder-fired weapons. Clearly, novel system designs incorporating recoil mitigating buffers or springs with appropriate recoil travel, as well as butt plate padding, will allow significantly greater projectile weights and velocities to be safely launched than currently accepted limitations would imply.

On the basis of this finding, claims made by TAC-WEAP personnel pertaining to the level of perceived recoil generated by their closed-breech, shoulder-fired weapon must be considered credible, within the accuracy of their testing methods. TAC-WEAP has claimed perceived recoil levels comparable to an M1 rifle or 12-gage shotgun for the projectile weights and velocities listed in Table 8. Of course, whether these recoil levels can be considered safe depends on individual tolerances for headaches and shoulder bruising and on whether gunners are wearing full combat equipment. Nevertheless, the recoil buffers employed in this system offer a tremendous improvement in recoil mitigation. Continued refinement of these mechanisms can only help to further reduce perceived recoil levels.

Table 8. Projectile Launch Parameters as Tested by TAC-WEAP Ventures, Inc.

Projectile Weight (lb)	Velocity (fps)	Momentum (lb-sec)
3	115-125	10.7-11.6
5	95-112	14.8-17.4
6	115-125	21.4-23.3

3. PRELIMINARY PROJECTILE DESIGN AND ANALYSIS

Following the recoil analysis, where it was assessed that projectiles of several pounds could be safely launched with a velocity above 100 fps, the next step in the system assessment was to begin sizing projectiles and evaluating their performance. It was kept in mind that the projectile requires some level of lethality and effective range in order to be useful. Projectiles within the caliber range of 90mm to 140mm (3.5 inches to 5.5 inches) that incorporate an explosive-loaded, shaped-charge warhead for armor penetration should provide reasonable lethality against light through medium armor threats, and for hardened bunker targets. Specific details of the performance of such a warhead are not addressed in this report since shaped-charge warheads are employed extensively in other ordnance applications of similar weight and size. At this point, we only need some idea of what projectile diameters, lengths, and weights to employ. A reasonable starting point for this analysis seemed to be a 90mm diameter projectile with a 4-pound weight budget. Both fin- and spin-stabilized projectile designs were considered since at this point we were uncertain which one would have the best aerodynamic performance characteristics.

A. PRELIMINARY WARHEAD SIZE AND WEIGHT BUDGET

The projectile designs began with the sizing of the warhead section.This analysis begins by designing a generic shaped-charge warhead projectile of 90mm caliber. Figure 4 shows the cross-section of a generic trumpet-shaped charge liner with a typical wall thickness and length to diameter for short-standoff, deep-armor penetration. This liner is made of copper and weighs 154 grams. In Figure 5, the explosive charge is added to the liner, bringing the weight up to 810 grams. In Figure 6, the warhead case, made of aluminum, is added to the design, bringing the total warhead section of the projectile to a weight of approximately 2 pounds.

The thickness of the warhead case ranges from 2 mm at the base of the boattail to 1 mm along the cylindrical forward portion. Using a standard 7075-T6 aluminum would provide more than adequate structural support to this warhead during launch and flight. The maximum projectile acceleration in the launch tube was estimated to be on the order of 1,600 g's. Assuming the explosive acts hydrostatically, like a fluid with no internal strength, a maximum wall stress of about 17,000 psi in the case would result. 7075-T6 aluminum is expected to have a yield strength of no less than 72,000 psi. Therefore, no detailed finite element analysis of this structure was performed since the case appeared to be adequately designed, even with such thin walls.

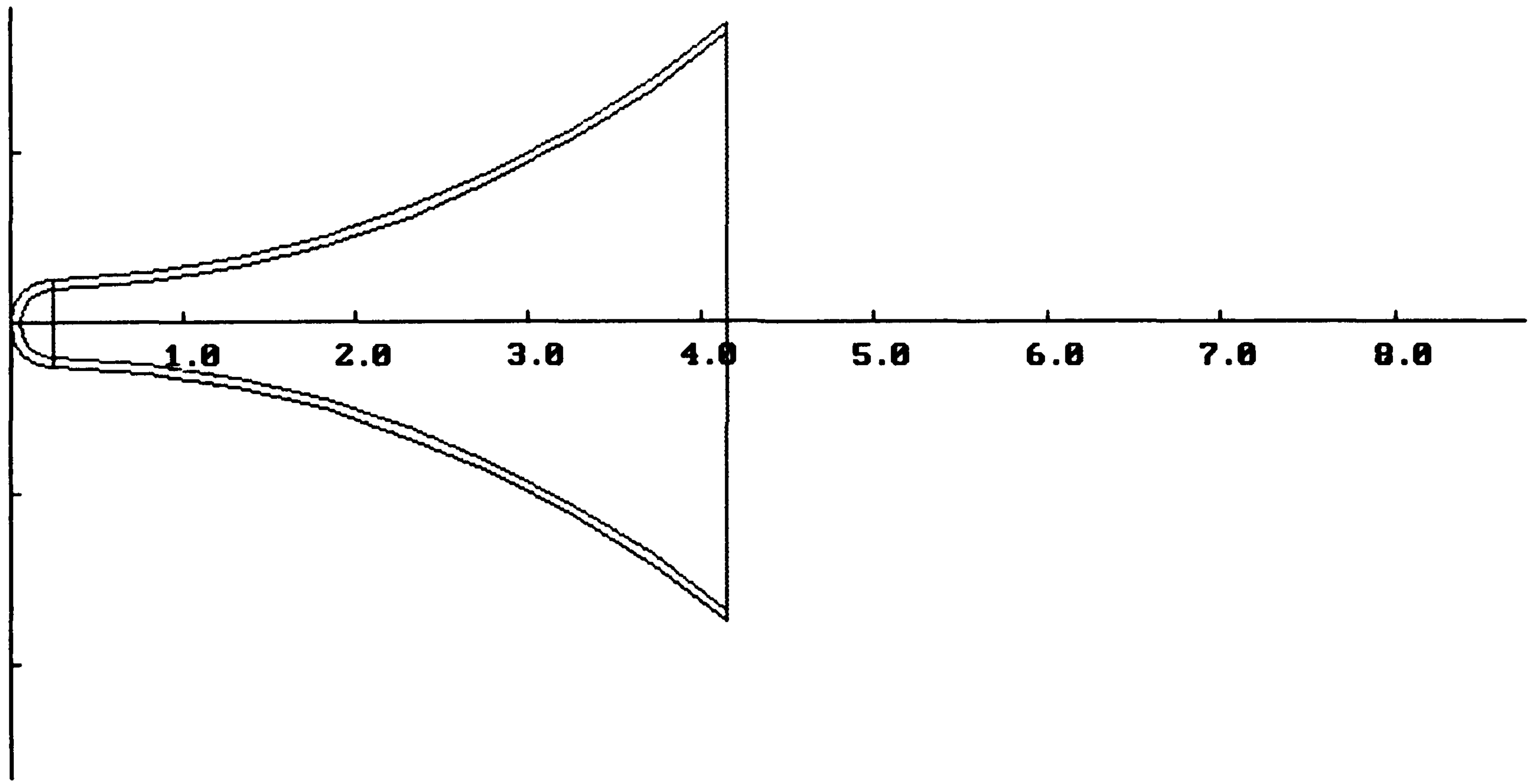

Figure 4. Generic Trumpet Liner for 90mm Warhead
(weight = 154 g)

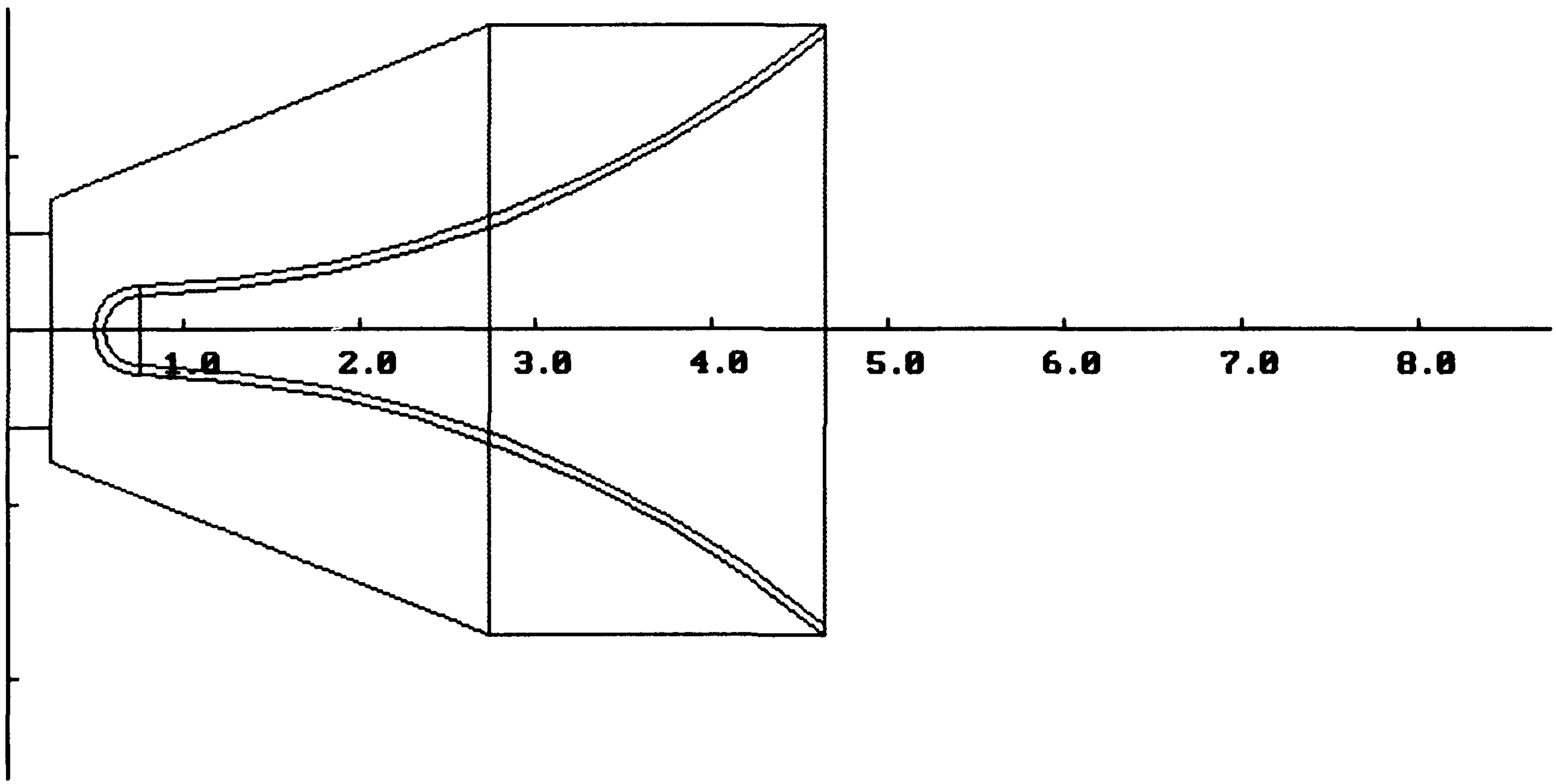

Figure 5. Explosive Liner Assembly for 90mm Warhead
(weight = 810 g)

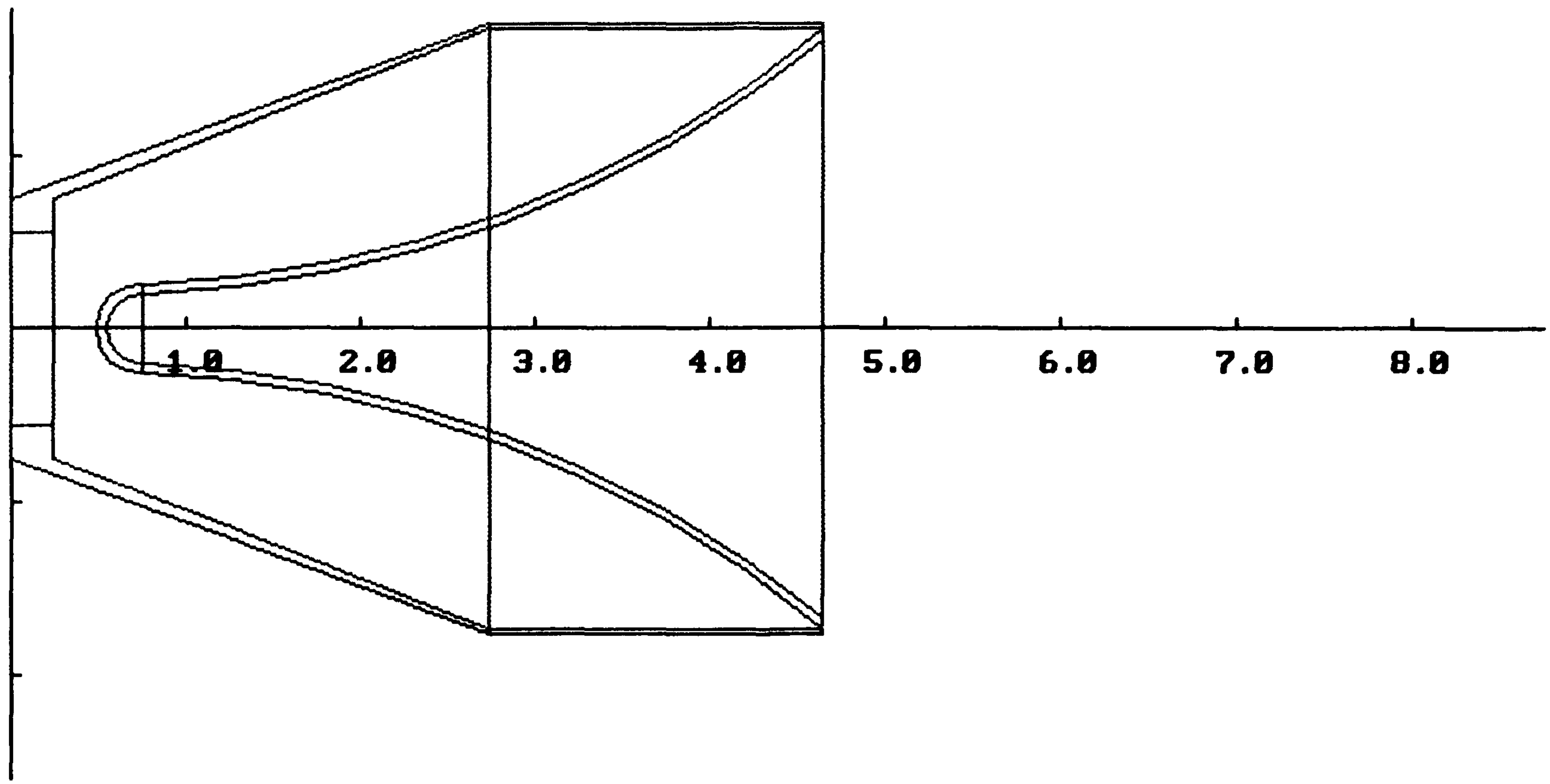

Figure 6. 90mm Warhead Section Assembly (Liner, Explosive, and Case) (weight = 2 lb)

B. PRELIMINARY INTERIOR BALLISTIC ANALYSIS

The acceleration estimates for the in-bore motion of the projectile were made by using a simplified model of the high-low pressure effect used in the launcher. The functioning of a high-low pressure launcher involves rapidly burning a small amount of propellant in a small high-pressure chamber and then releasing the combustion gases into a larger low-pressure tube to accelerate the projectile. The advantages of this type of launcher are that a small amount of propellant can be used to launch relatively large, heavy projectiles at modest muzzle velocities without the need for a heavy launch tube.

Propellants burn with greater consistency and very rapidly under high pressure and when used in a gun must burn rapidly to force the projectile out of a short tube with adequate muzzle velocity and in a timely manner. The high-pressure chamber, therefore, is where the propellant is ignited and allowed to rapidly burn. When all or nearly all of the propellant is consumed, the high-pressure chamber releases the gases through a rupture disk, and the high pressure reservoir bleeds into the low-pressure chamber behind the projectile, forcing it down-bore.

To model the interior ballistics of the high-low pressure chamber, we worked backwards from the desired muzzle velocity to the amount of pressure the high-pressure chamber would have to generate. We assumed that all of the propellant would be consumed in the high-pressure chamber before release and that the resulting low pressure would drop adiabatically (with no heat loss) as the projectile traveled down-bore. Adiabatic expansion is a reasonable assumption as long as the action time is very short. In this case, we expected the projectile to leave the barrel within several milliseconds. Adiabatic expansion is described by the following equation:

$$pV^k = constant, \qquad (6)$$

where p = pressure, V = volume, and k = ratio of specific heat at constant pressure to specific heat at constant volume (Cp/Cv) for the combustion gases, typically about 1.2 to 1.3 for standard propellants.

Using a barrel length of 24 inches, a total projectile weight of 4 pounds, and a maximum pressure in the low-pressure tube of 652.5 psi, the muzzle velocity achieved was 140 fps. Figures 7 and 8 show the velocity history for the projectile and the acceleration and pressure histories, respectively. To achieve an initial 652.5 psi in the low-pressure tube requires approximately 12,000 psi in a 1-in^3 high-pressure chamber, which is certainly realistic. Although in practice the high-pressure chamber would be designed to give a more efficient smooth and flat acceleration to the projectile, this analysis shows in a conservative manner that such a system is, nevertheless, feasible.

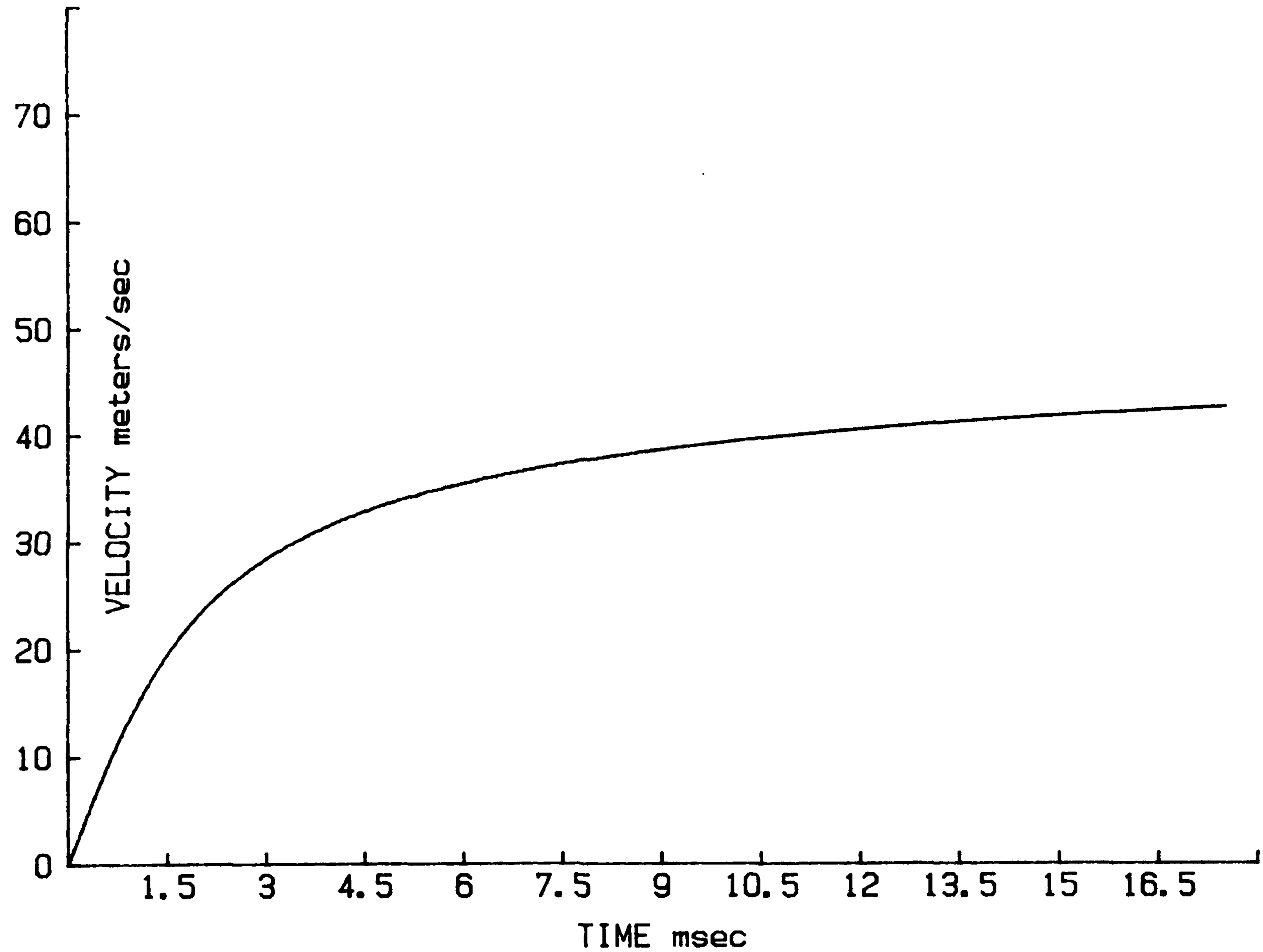

Figure 7. Velocity History for High-Low Pressure Launcher

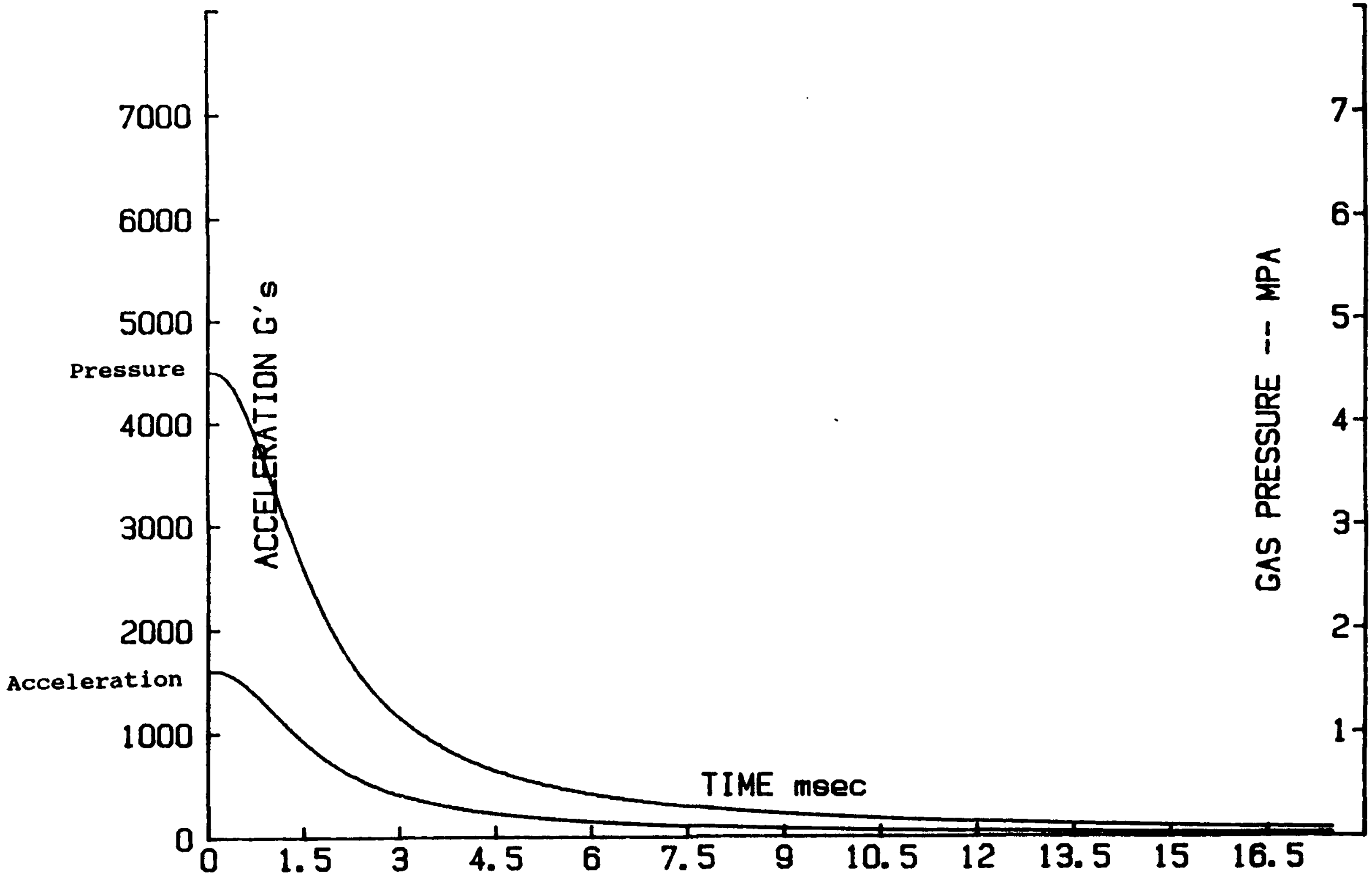

Figure 8. Acceleration and Pressure Histories for High-Low Pressure Launcher

C. PRELIMINARY BOOST-ROCKET-MOTOR DESIGN AND ANALYSIS

With a launch velocity of 140 fps, a boost rocket motor is a requirement for achieving any significant projectile range. Several important performance parameters, however, affect the size and weight of the rocket motor employed. The first step in sizing the rocket motor is to decide to what velocity the projectile should be boosted. From experience, it seemed reasonable to remain subsonic, since traversing the high-drag trans-sonic region is very costly in terms of thrust and requires a proportionally larger motor for every increment in velocity achieved. Considering that the motor is basically parasitic to the terminal effects of the projectile, the motor weight should be kept to a minimum; therefore, remaining subsonic would be congruent with this thinking. Looking at the problem from the other direction, it is desirable to keep the time of flight as low as possible so target movement does not adversely degrade hit probability. Therefore, a reasonable boost velocity was chosen in the neighborhood of 900 fps in the high subsonic region.

Typical solid propellants have a specific impulse in the neighborhood of 240 seconds (or lb-sec/pound). This term means that 1 pound of propellant will give approximately 240 lb-sec of impulse or velocity change to a given rocket weight. This is a convenient propellant parameter to use in sizing the rocket motor, even though it does not describe the propellant geometry or how it is consumed in getting to the burnout velocity. Getting a 4-pound projectile from 140 fps to 900 fps, therefore, will require approximately 0.4 pound of propellant:

$$\frac{(900-140)*(4/32.2)}{240} = 0.4\ lb \tag{7}$$

The total weight of the rocket motor can be greatly affected by the weight of the combustion chamber. This weight is driven by the chamber-wall thickness and geometry, which in turn is driven by the chamber pressure and mass flow rate of the rocket, which gives the motor thrust. The most volumetrically efficient motor case is one with a length to diameter of 1. This geometry gives the greatest internal volume for the smallest case surface. However, this may not be the least mass case if the motor must operate at high pressure to achieve the desired thrust. Operating the motor at high pressure requires a thicker case wall and hence more case weight. However, for the same amount of thrust at lower pressure, the propellant grain must have a larger burning surface. This forces the case to be long and of smaller diameter, which, in turn, gives a greater case surface area. The geometry tradeoffs for the rocket motor, therefore, are highly nonlinear.

Following determination of the amount of propellant required in the motor, the next motor parameters to establish are thrust profile and burn time. There is an optimal burn

time and thrust history for an externally boosted projectile based on the need to minimize dispersions due to wind and thrust misalignment. The stability of the projectile also plays a key role in reducing these dispersion sensitivities. Since most of the angular dispersion of a projectile will occur during the first yaw oscillation, the burn time should carry over several yaw oscillations to avoid adding to the dispersion during rocket boost when the projectile is pointing off of the intended flight axis. This will result in the off-axis thrust being more or less balanced from one side of yaw to the other. In light of this, however, there is an optimal wavelength of yaw for reducing dispersion sensitivity to wind and thrust misalignment. If the yaw oscillation rate is too high, indicating high static stability of the projectile, the sensitivity to wind increases. However, with high static stability, the sensitivity to thrust misalignment decreases. A low yaw oscillation rate, on the other hand, also means that the motor must burn longer and with lower thrust to avoid boost-phase dispersions.

This is a very involved tradeoff analysis, further complicated by the fact that the projectile has yet to be defined in great enough detail to determine its yaw oscillation wavelength and rate. This is a function of its aerodynamic characteristics, which are based on the projectile geometry and mass parameters. Therefore, the rocket motor analysis began by choosing what seemed to be a reasonable burn time and thrust for a projectile of this size. Using 0.4 pound of propellant of specific impulse 240 yields a total impulse of 96 lb-sec, which is approximately 200 pounds of thrust for a burn time of 0.5 second. The rocket motor geometry was sized based on these initial parameters. Table 9 shows the tradeoff in motor case weight based on the operating pressure and case geometry for generating 200 pounds of thrust for 0.5 second with 0.4 pound of propellant. A safety factor of 20 percent was added to the operating pressure of the motor, and the motor case material was chosen as 7075-T6 aluminum. The structural analysis of the case wall was performed using the closed form equations for a thick wall pressure vessel and the von Mises failure criteria. The propellant grain was designed to give a constant thrust and pressure, hence the burning surface remained constant. Basic grain geometries for constant thrust, pressure, and burning surface include the internal star, rod in tube, and hollow rod.

Table 9 shows that longer, reduced-diameter rocket motors will weigh less since they can operate at lower pressure; this will result in much thinner wall thicknesses. There is a reasonable minimum wall thickness for practicality in manufacturing the rocket motor, and the motor length should not be unreasonably long for packaging and aerodynamic considerations. For this reason the 4-inch-long motor with 1.5-inch diameter was chosen as a good baseline for this projectile design. A wall thickness of 1 mm (0.04 inch) was considered reasonable for this rocket motor.

Table 9. Rocket Motor Weight Tradeoffs (200-lb Thrust for 0.5 sec)

Case Length (in)	Diameter (in)	Thickness (in)	Operating Pressure (psi)	Weight (lb)
1.78	2.25	0.096	7430	0.218
4.00	1.50	0.031	3900	0.073
9.00	1.00	0.013	2400	0.039
28.00	0.56	0.003	1020	0.016

D. CANDIDATE GENERIC FIN-STABILIZED PROJECTILE DESIGNS

Figure 9 presents a cross-section of the assembly of the first generic 90mm projectile design. The warhead section is fitted with a thin conical ogive, which may function as a double-ogive impact sensor or incorporate a piezoelectric impact switch on the tip. The base of the warhead section is fitted with a safe-and-arm fuze mechanism, which has the rocket motor attached to its base. The fuze mechanism has not been designed in detail in this analysis. However, a weight budget of 0.2 pound in a volume of 2 in^3 was considered sufficient for this type of projectile. For example, the fuze mechanism for the M72 LAW weighs 0.15 pound in a volume of approximately 2.4 in^3.

This projectile design weighs a total of 2.85 pounds, which is 29 percent less than what was expected prior to its development. There exists, therefore, some room for weight growth. The method of stabilization for this design is the use of ring-tail fins—six rectangular fins with a circumferential ring connecting the tip cord of each fin. This gives a large bore-riding wheel base between the fin section and the cylindrical portion of the warhead section. A long wheel base is important to maintaining stability of the round in-bore. The drag coefficient of this projectile at subsonic velocities is about 0.34 and its static margin is about 0.30 caliber. Three alternate nose-shape configurations were also considered for this projectile design, as shown in Figures 10, 11, and 12. Each nose change gives more or less drag and more or less static stability than the baseline design in Figure 9. All of these configurations weigh approximately 3 pounds. Table 10 compares the aerodynamic parameters of each design in the subsonic velocity region.

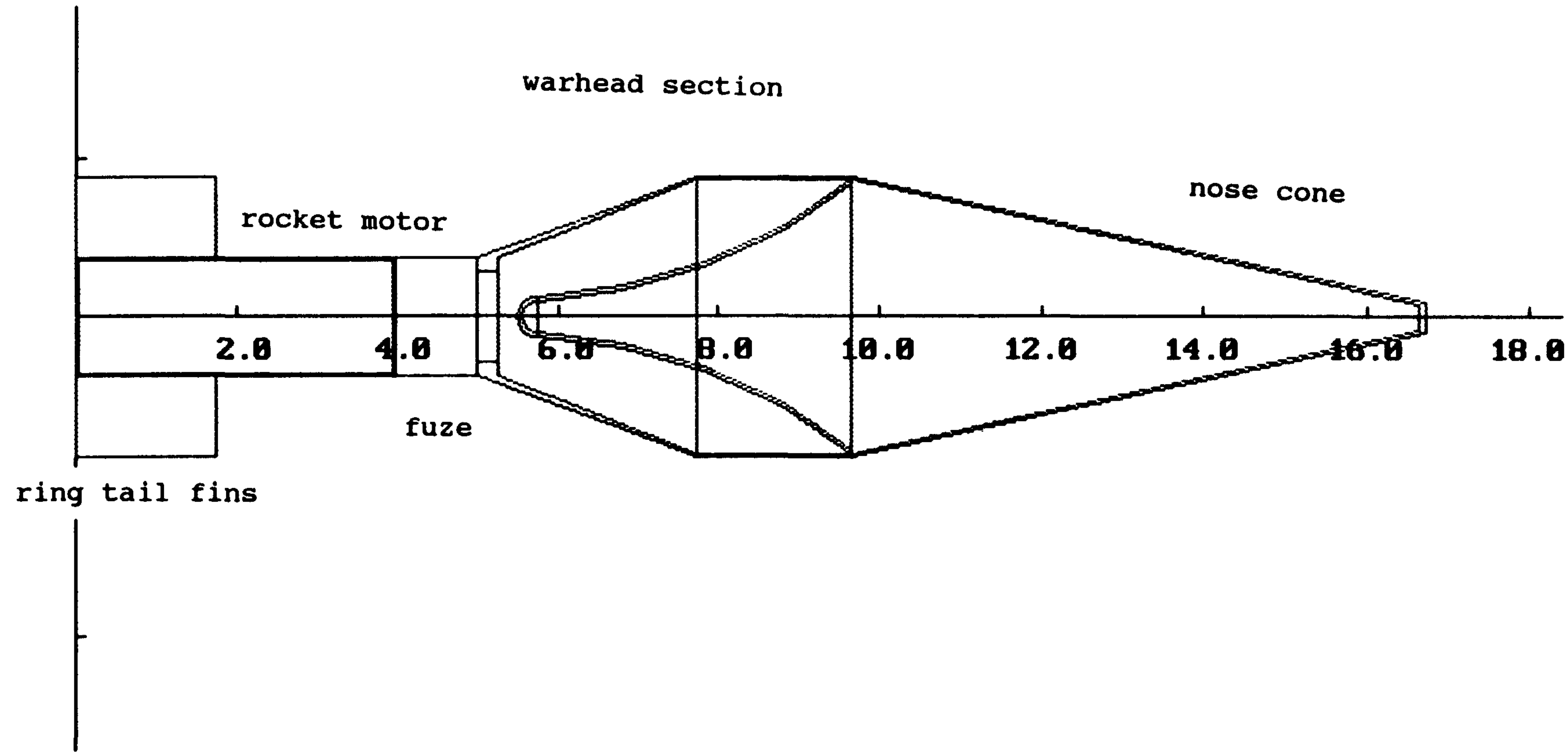

Figure 9. Generic 90mm Fin-Stabilized Projectile (weight = <3 lb)

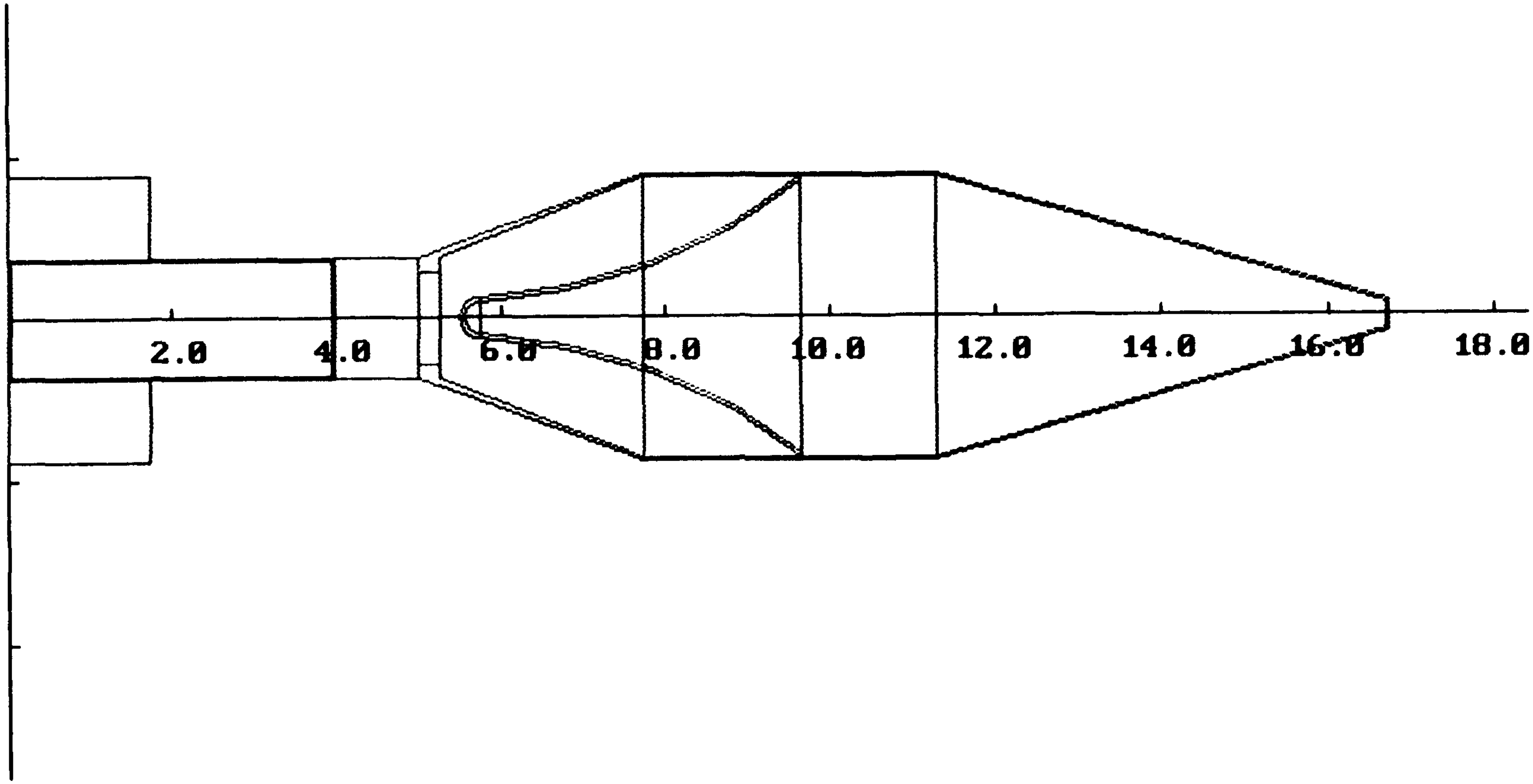

Figure 10. Alternate Nose Configuration #1 for 90mm Projectile

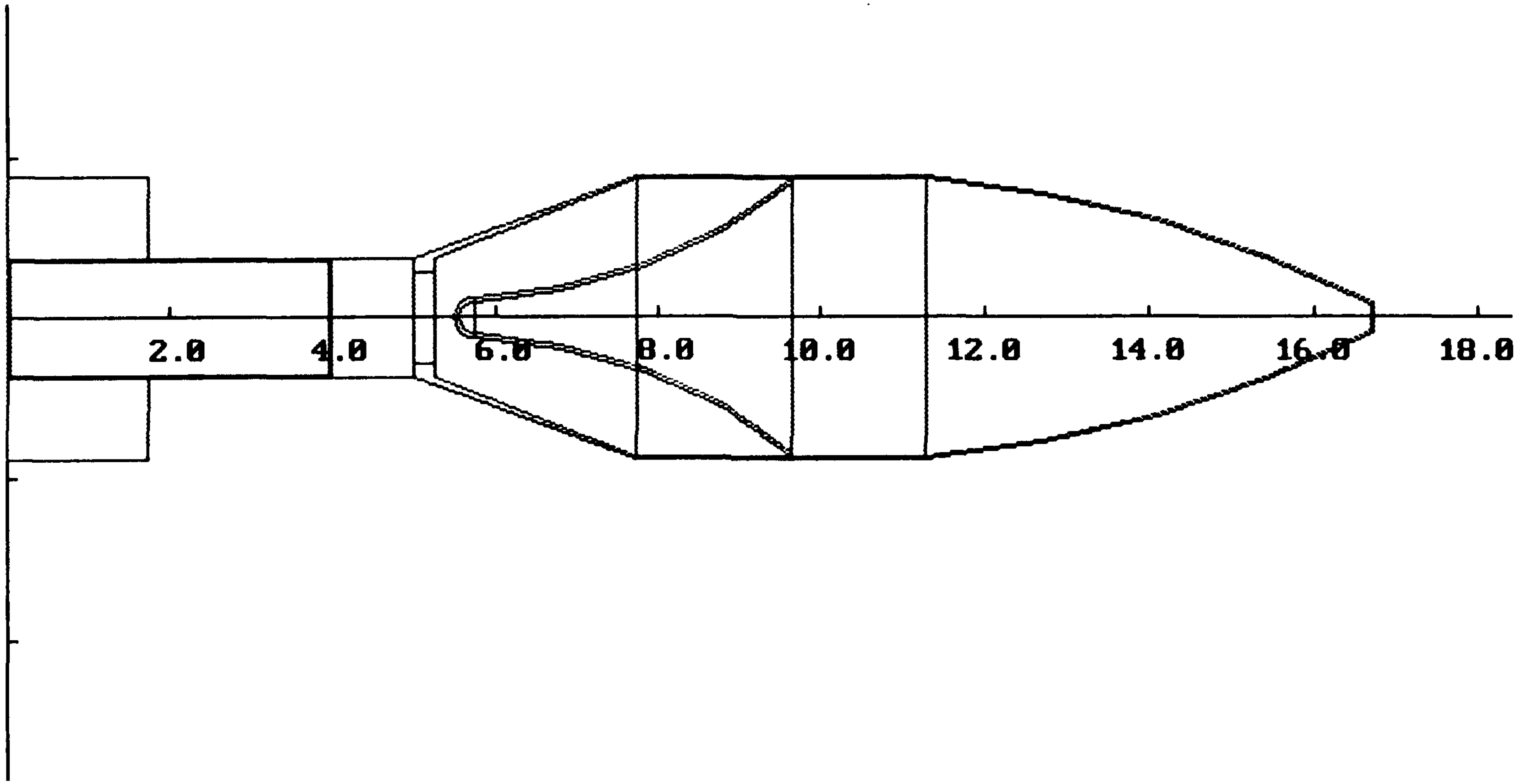

Figure 11. Alternate Nose Configuration #2 for 90mm Projectile

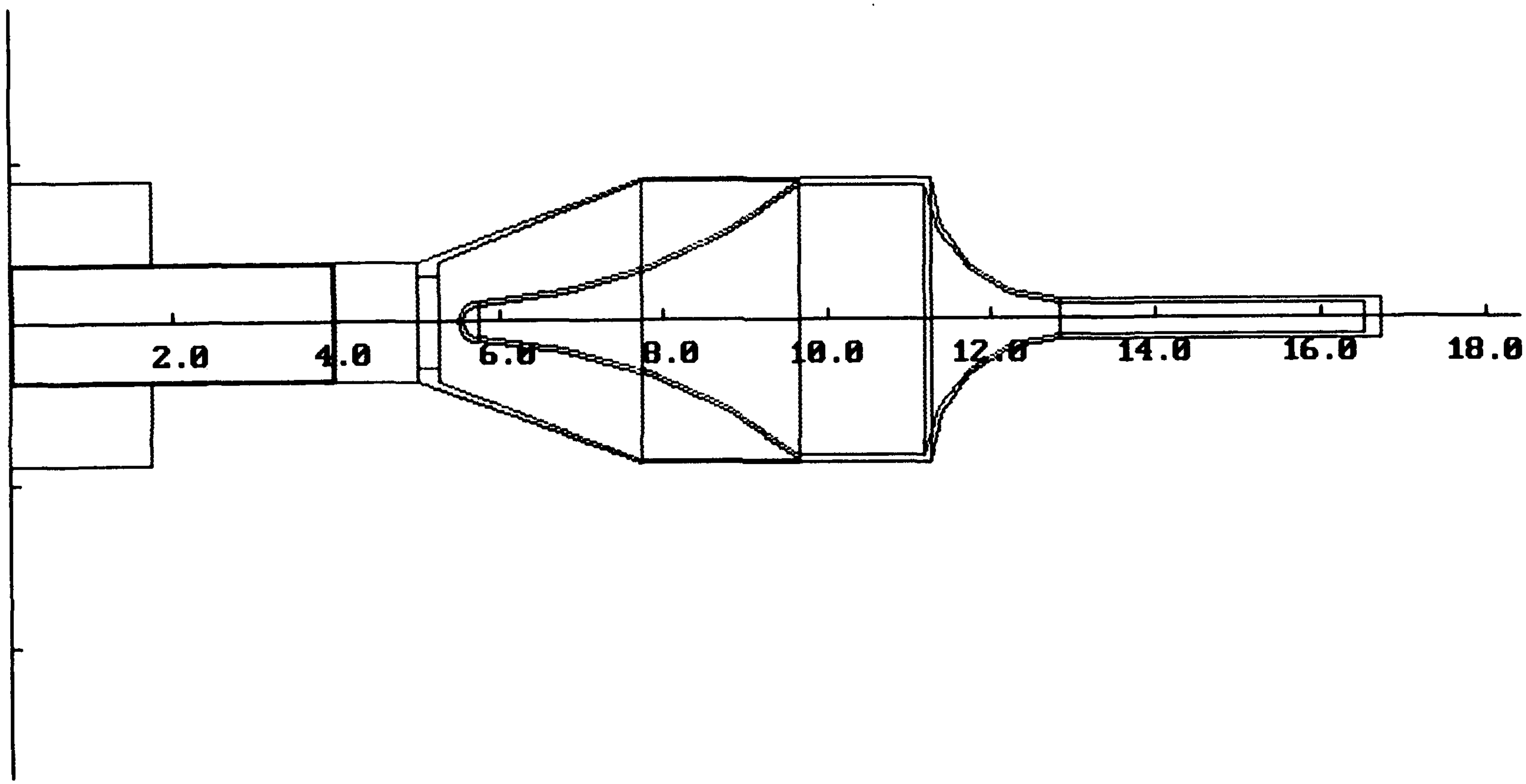

Figure 12. Alternate Nose Configuration #3 for 90mm Projectile

Table 10. Subsonic Aerodynamic Comparisons for Candidate Fin-Stabilized Designs

Type	Drag Coefficient	Static Margin (caliber)	Wavelength of Yaw (ft)
Baseline	0.34	0.30	72.4
Nose 1	0.33	0.10	129.0
Nose 2	0.33	0.13	118.0
Nose 3	0.36	0.36	69.2

For the baseline design, with a muzzle velocity of 140 fps and a yaw wavelength of 72.4 feet, the first yaw cycle will take about 0.52 second. The initial choice of 0.5 second of burn time for the rocket motor, therefore, turns out to be a good one. The yaw oscillation rate will, of course, increase as the projectile gains velocity due to boost, so the burn time could be reduced proportionally. Nevertheless, the current burn time is adequate to reduce boost-phase dispersion errors. The changes in nose shape give different aerodynamic characteristics, most notably lower static stability with the shorter noses and larger yaw wavelengths as compared to the spike nose and baseline designs.

E. CANDIDATE GENERIC SPIN-STABILIZED PROJECTILE DESIGNS

Generic spin-stabilized projectiles were designed based on the warhead and rocket motor parameters (described in previous section) to evaluate whether there may be aerodynamic and trajectory advantages to this method of projectile stabilization. Figures 13 and 14 present the results of attempting to design spin-stabilized projectiles with a reasonable weight. Removing the fin section on the earlier designs results in a statically unstable projectile. To overcome this problem, the projectile must spin to achieve gyroscopic stability and ensure that the nose always precedes the tail during flight. Even with a spin rate of one turn in 15 calibers, which is near the upper limit of reasonable spin rates, the projectile designs, as they were configured with fins, were gyroscopically unstable upon leaving the muzzle. To change this condition, the ratio of the axial moment of inertia to the transverse would have to increase, or the static margin would have to increase by shifting the center of gravity forward or the center of pressure rearward, or a combination of the three would be required. Each of the two designs (Figures 13 and 14) represents a compromise that took into consideration changes to all three of these gyroscopic stability parameters.

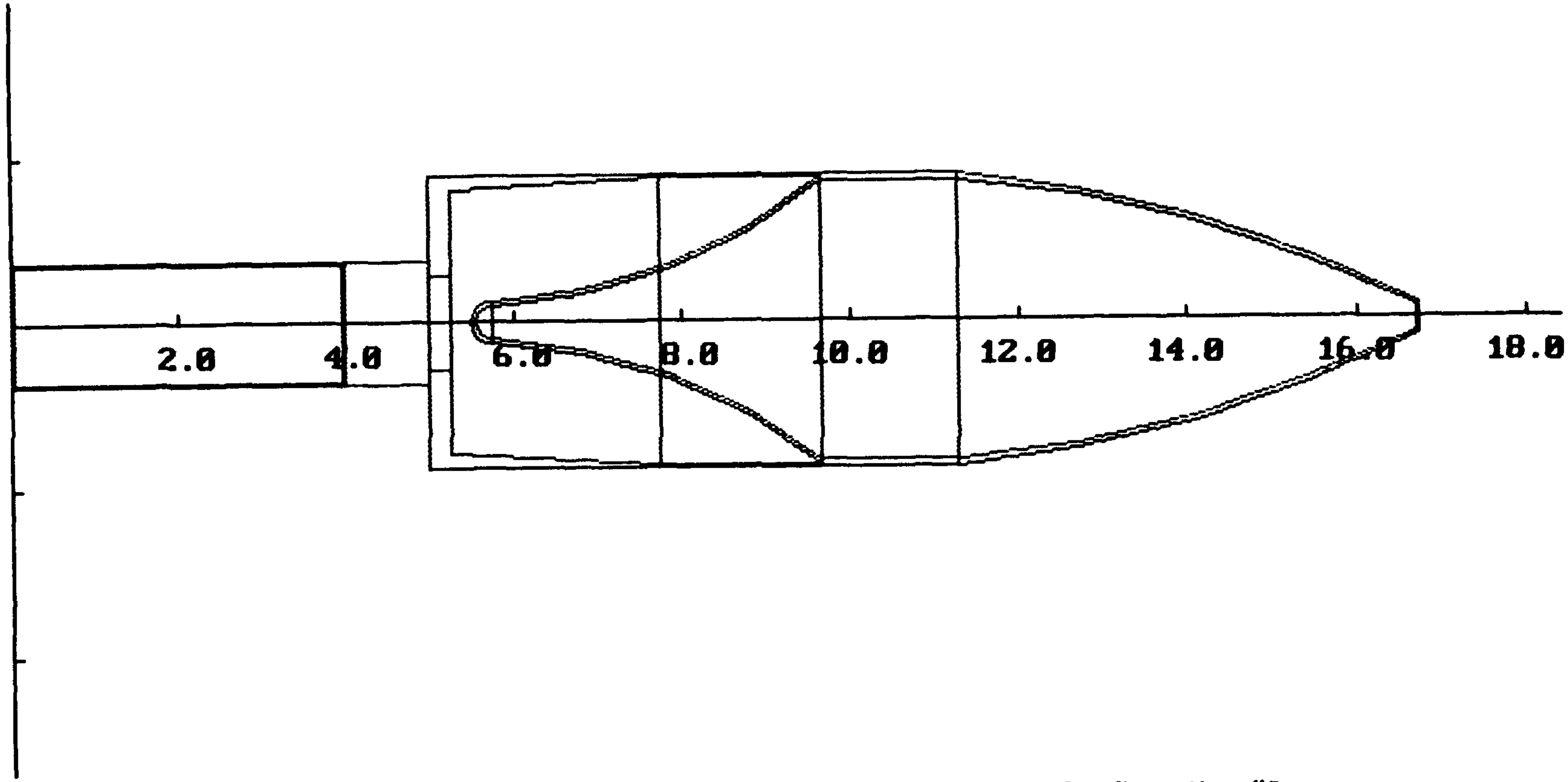

Figure 13. 90mm Spin-Stabilized Projectile With Nose Configuration #2
(weight = 4 lb)

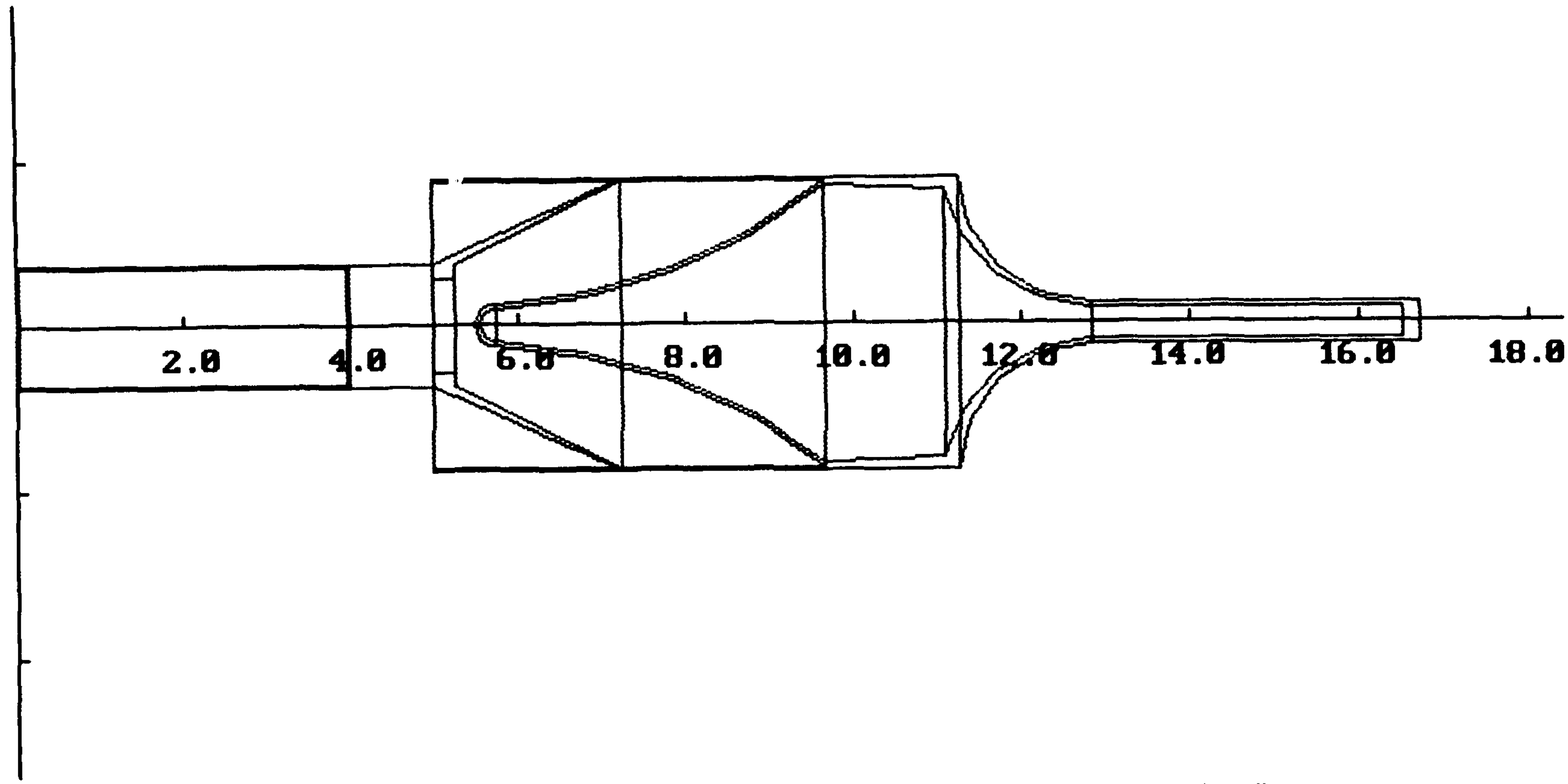

Figure 14. 90mm Spin-Stabilized Projectile With Nose Configuration #3 (weight = 3.3 lb)

In Figure 13, the base of the projectile is increased to full caliber, thus eliminating the boattail and adding considerable weight to the central portion of the projectile. Elimination of the boattail shifts the center of pressure slightly to the rear, and the added weight about the center of gravity has the effect of greatly increasing the axial moment of inertia without greatly affecting the transverse moment of inertia. Weighing in at about 4 pounds, this projectile is gyroscopically stable at air temperature down to -45°C for subsonic flight velocities.

In Figure 14, the spike nose shifts the center of pressure to the rear, as does elimination of the boattail by adding a cylindrical skirt over the aft end of the projectile. The cross-section of the spike-nose windshield is thickened to add weight to shift the center of gravity forward, and the boattail of the explosive charge is made shorter to add axial inertia and weight around the center of gravity as well. This projectile design is also gyroscopically stable down to -45°C in subsonic flight, but its weight is more in line with the fin-stabilized versions. The spike-nose projectile has slightly more drag compared to the ogive-nose version—C_d 0.21 versus 0.185—but both have lower overall drag compared to the fin-stabilized designs. The much longer cylindrical bore riding surfaces of each will also provide good in-bore stability during launch.

F. SCALING UP OF PROJECTILE DESIGNS

The starting point for the projectile design and analysis was a 90mm projectile with a weight of approximately 4 pounds. For the fin-stabilized designs developed here, a maximum 3-pound weight was achieved. The spin-stabilized designs were slightly heavier, with one reaching the 4-pound limit estimate. All projectiles were designed to a length of 16.7 inches. The practicality of scaling these designs up to greater projectile diameters was assessed to determine how much lethality growth potential exists in this weapon system.

Experience has shown that the weight of a projectile, when scaled up proportionally, will increase directly with the increase in diameter squared times the increase in length, according to the following relationship:

$$\frac{W2}{W1} = \frac{D2^2 * L2}{D1^2 * L1} \qquad (8)$$

when L1/D1 = L2/D2.

The length-to-diameter ratio of the current designs are about 4.71. Scaling the finned designs to 110-mm diameter would make the length about 20 inches, and, according to the above scaling relationship, the weight would increase from 3 pounds to 5.4 pounds. Making

the projectile much longer than 20 inches may become impractical if reasonably short launcher tube lengths are desired. The projectile diameter could still be increased without increasing projectile length if adequate stability can be designed into a modified fin section. Details of such modifications will not be presented here, but they may include fold-out fins and the like. Further increasing the diameter to 125 mm and keeping the length a constant 20 inches will make the projectile weight increase to about 7 pounds. This was calculated based on the weight of the 110-mm projectile, and keeping L2 equal to L1 in the scaling equation. This weight projectile may be pushing the limit for safe recoil levels if launched with a velocity much over 100 fps. For this reason, the scaling investigation will stop here. A suggested reasonable limit for the caliber of this type of weapon may be in the 125-mm-diameter range based on our current understanding of recoil.

G. STABILITY ANALYSIS OF SPIN-STABILIZED DESIGNS

Although the spin-stabilized designs discussed above achieved gyroscopic stability, they failed to maintain dynamic stability. Whereas gyroscopic stability is a function of the spin rate and the moments of inertia compared to the aerodynamic pitching moment, dynamic stability is a much more complicated condition based on the gyroscopic stability as well as the moments of inertia compared to the projectile drag, normal force, magnus force, and pitch-damping moment. Without dynamic stability, a gyroscopically stable projectile will still not fly correctly. In the case of these spin-stabilized designs, the projectiles have slow mode or precession instability. In other words, the projectiles are gyroscopically stable but precess about an axis that is not the flight path of the projectile.

Figures 15 and 16 show this condition of dynamic instability in graphic form from the output of 6-degree-of-freedom trajectory simulations. Both the ogive-nose and spike-nose designs, Figures 15 and 16, respectively, were launched at 45 degrees super-elevation with an initial velocity of 140 fps and an initial spin rate of 200 rad/sec, representing a twist rate of one turn in 15 calibers. To accentuate the epicycle motion of the projectile flight, a 1-degree initial total yaw angle was imposed at the muzzle, shown as 0.7071-degree left yaw and 0.7071-degree pitch-down in the figures. The simulations were run for 2 seconds, and these figures show the trace of the movement of the projectile nose about the flight axis of the projectile, represented as the origin of the graph axes. The observer is looking forward from the launch point to the impact point along the trajectory. Clearly, the projectile nose is tracking further off to the right after each precession cycle, despite the gyroscopically stable nature of the nutation cycles. The boost rocket motor was not employed in either of these simulations, so both the velocity and spin rate of the projectile slowly decayed.

Analyzing the relationship between gyroscopic and dynamic stability, it was observed that dynamically stable flight could be achieved if very high gyroscopic stability was imposed on the projectile. High gyroscopic stability could be realized by using the rocket motor to

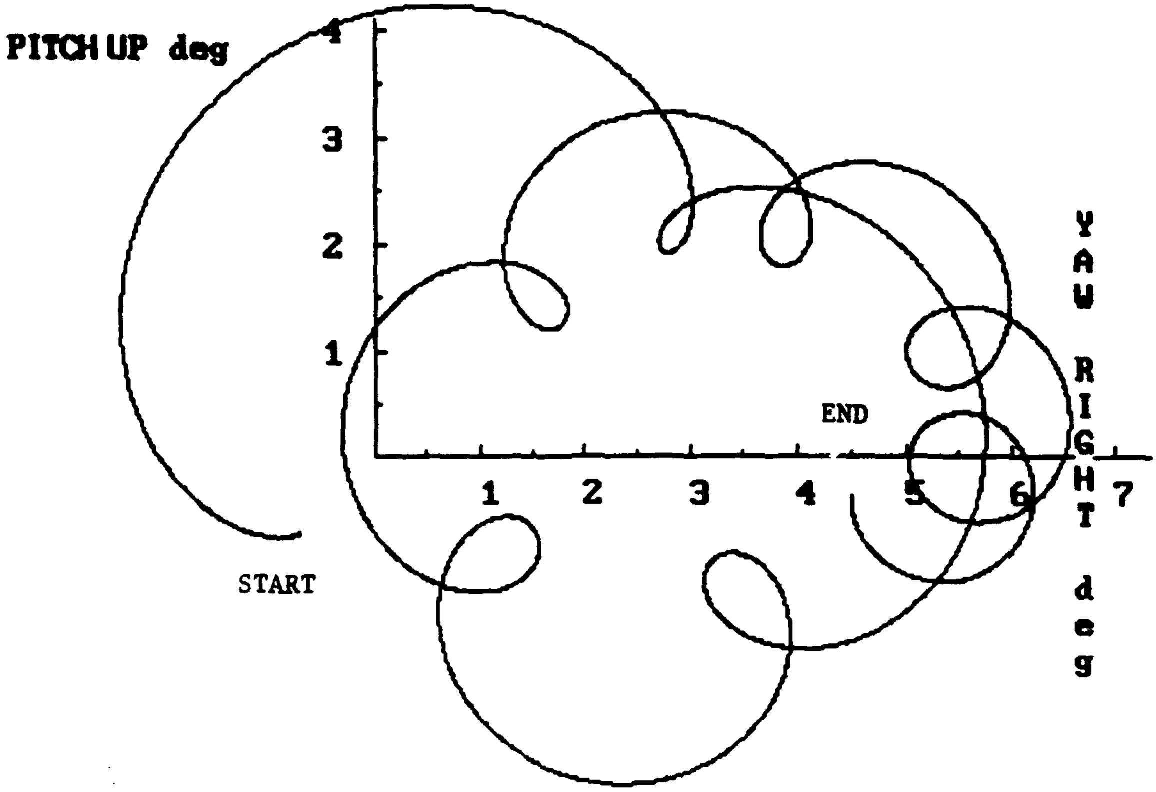

Figure 15. Epicycle Motion of Ogive-Nose, Spin-Stabilized Projectile

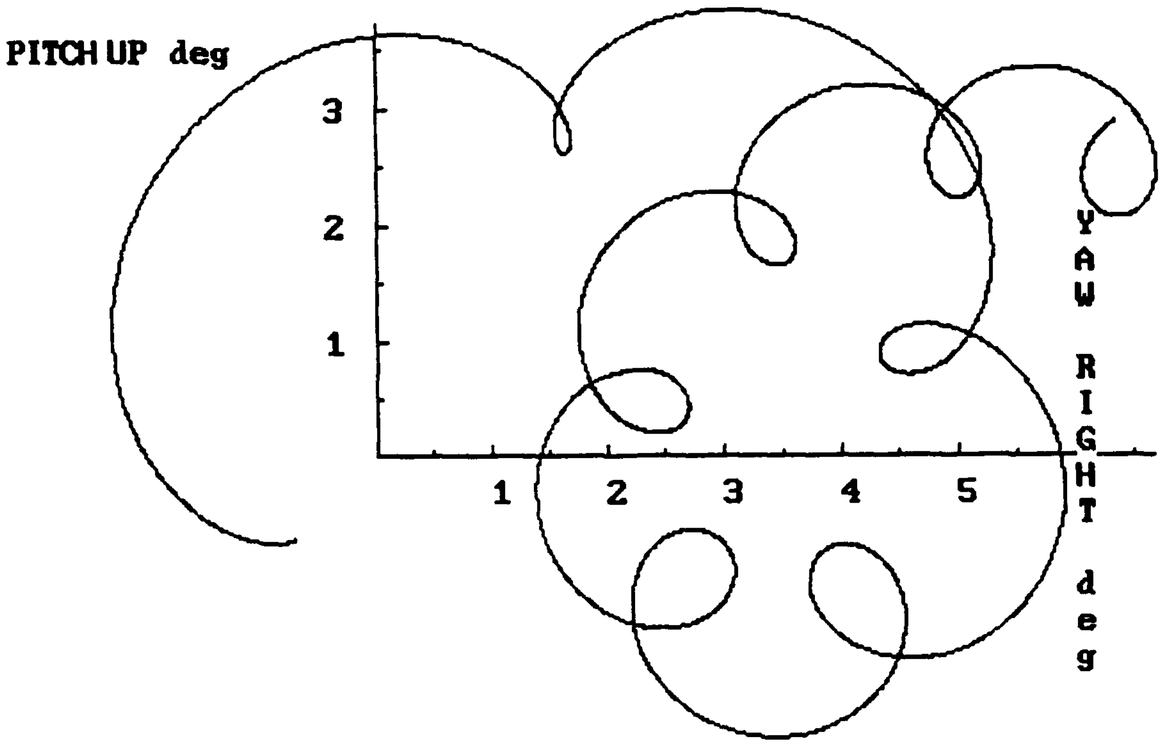

Figure 16. Epicycle Motion of Spike-Nose, Spin-Stabilized Projectile

spin the projectile up to a very high spin rate. This could be performed simply by canting the multiple rocket nozzles slightly and locating them off of the central axis of the projectile. In this manner, the rearward thrust would also provide a torque to spin up the projectile. Figure 17 shows the results for the spike-nose projectile for the same initial launch conditions when the rocket motor is employed to boost its velocity as well as spin up its rotation. The motor was initiated at 0.04 second, or approximately 6 feet from the muzzle, and it provided 194.2 pounds of axial thrust and 2 ft-lb of torque for a burn time of 0.5 second; 2 ft-lb of torque represents 47.8 pounds of thrust oriented 13.8 degrees off axis at a radius of 0.5 inch from the projectile centerline. The total thrust, therefore, for the motor was 200 pounds. In this simulation, the rocket motor increased the projectile spin rate to a maximum of about 1,100 rad/sec, and the dynamic instabilities seen previously have disappeared. The projectile is ultimately following a stable trajectory to the target.

Analysis along these lines continued, and the rocket motor spin-up parameters were modified to improve the trajectory. The initial condition of yaw was also reduced to 0.5-degree maximum muzzle jump based on the long bore-riding surface of the projectile. Ultimately, the analysis resulted in a rocket thrust of 175 pounds in the axial direction with 4 ft-lb of torque, which produced a maximum spin rate of about 2,000 rad/sec. Figure 18 shows the resulting epicycle motion for a 2-second trajectory. For this time of flight, the projectile reached a range of 1,560 feet with a super-elevation of only 5 degrees.

Unfortunately, the projectile showed a lateral drift of 11.3 feet. This is a little disconcerting, since to hit a target at any significant range would required considerable aim to the side. To assess the dispersion effects of this lateral drift on the muzzle jump condition, the initial yaw angle was shifted 180 degrees to the right and up. This is reasonable to do, since the muzzle exit conditions will be random in reality. Figure 19 shows the epicycle motion for this initial condition and trajectory. At 1,560-foot range, however, the projectile drifted 31.6 feet. This represents a radial dispersion about the midpoint of at least 10 feet at 1,560-foot range, or about 6.4 mils angular dispersion, which is a serious problem. Such a large dispersion makes hitting a point target virtually impossible at this range.

H. TRAJECTORY ANALYSIS OF FIN-STABILIZED DESIGNS

Rather than continue to further refine the trajectory of spin-stabilized projectiles, analysis shifted to evaluating the fin-stabilized versions to see if they could be easily shown to perform significantly better. The baseline fin-stabilized design was chosen for the bulk of the analyses since it seemed like a good middle-of-the-road compromise between the other configurations. Analysis began with the same thrust parameters as for the latest spin-stabilized design (i.e., an axial thrust of 175 pounds and a spin-up torque of 4 ft-lb). Initial spin-rate conditions at the muzzle were set to 0.1 rad/sec, and the fins were given a cant

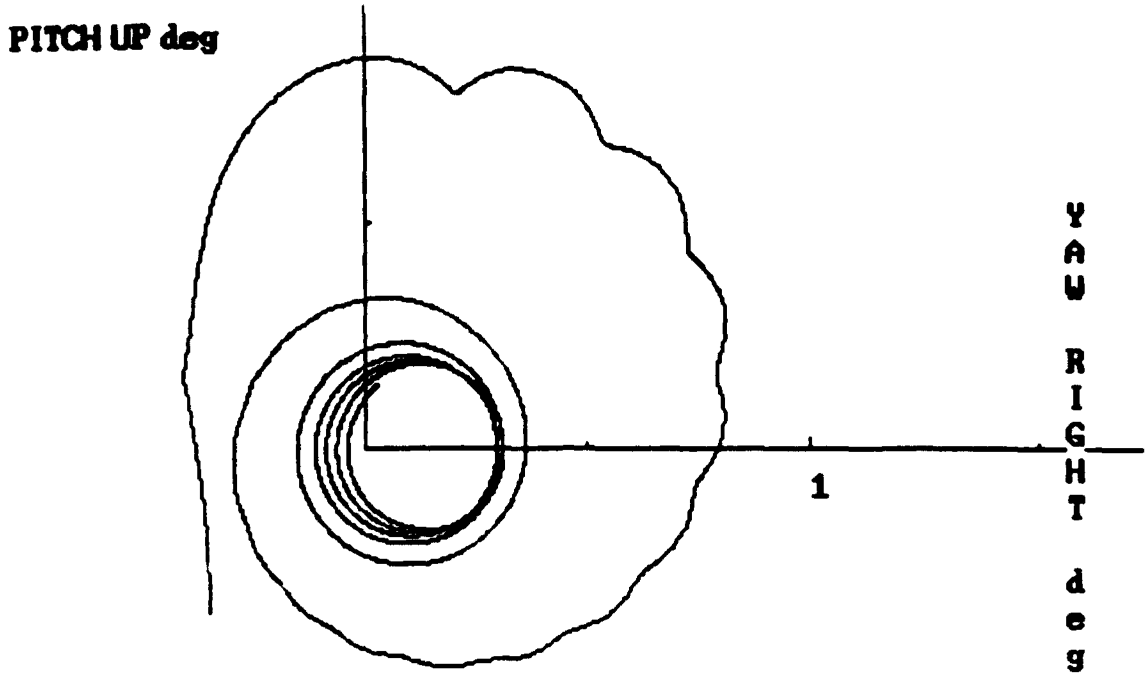

Figure 17. Epicycle Motion of Spike-Nose Projectile Incorporating Boost and Spin-Up Rocket Motor (1-second trajectory)

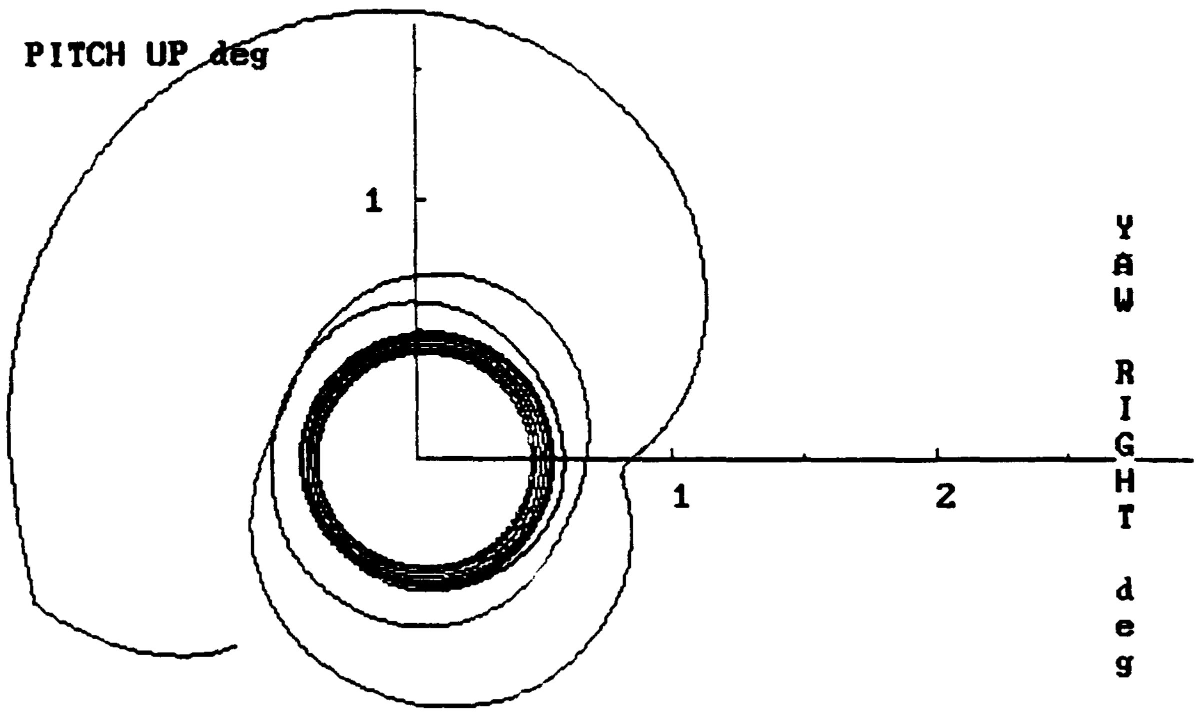

Figure 18. Epicycle Motion of Spike-Nose Projectile Incorporating Boost and Spin-Up Rocket Motor (2-second trajectory)

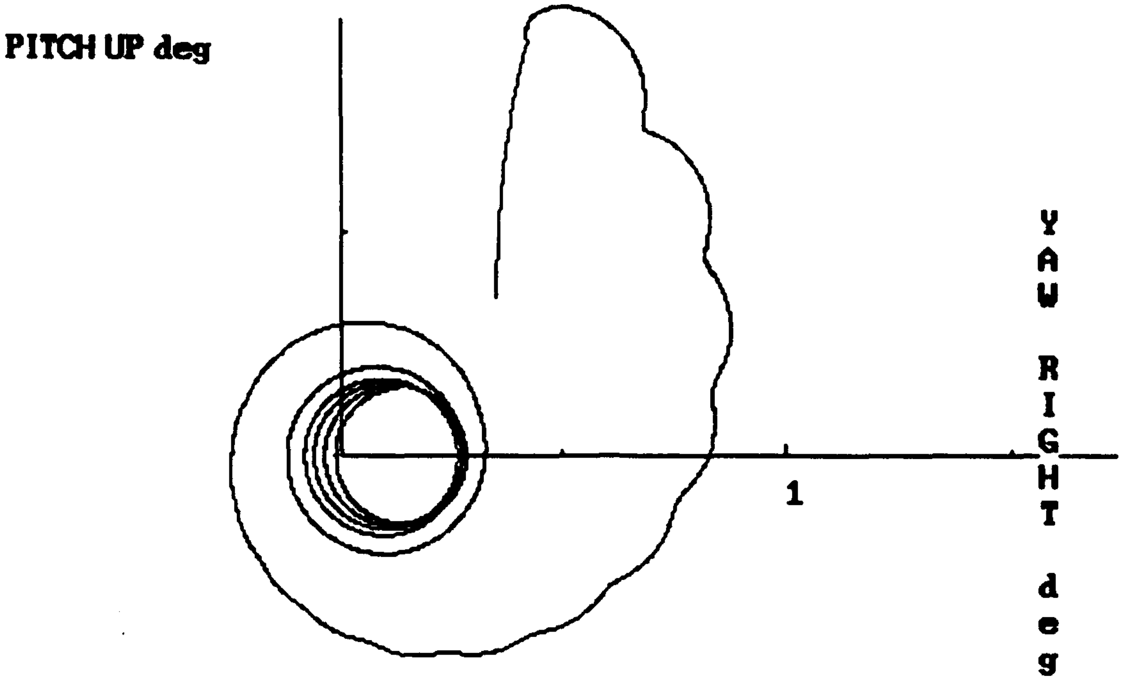

Figure 19. Effect of Shifting the Initial Condition of Yaw on the Epicycle Motion

angle of 0.1 degree. This should generate sufficient spin to mitigate any thrust misalignment effects without inducing unacceptable drift in the trajectory. Figure 20 shows the resulting epicycle motion for the fin-stabilized projectile. The initial yaw angle quickly dampens out as the projectile increases in forward velocity. However, the projectile hangs up in the second quadrant for quite some time during damping. The result is a lateral drift at 1,540-foot range of 14.2 feet.

The rocket motor and spin parameters were then revised to see if lateral drift could be brought under control. All motor torque was eliminated, making the axial thrust 200 pounds, resulting in the motion in Figure 21. The resultant drift became only 1.9 feet at 1,630-foot range. The maximum projectile spin rate due to fin cant was also only about 14 rad/sec. Clearly, a slowly spinning projectile will have less lateral drift. The thrust profile was then changed by decreasing the thrust to 100 pounds, but increasing the burn time to 1 second to keep the total impulse constant. The resulting drift was only 0.8 foot at 1,544

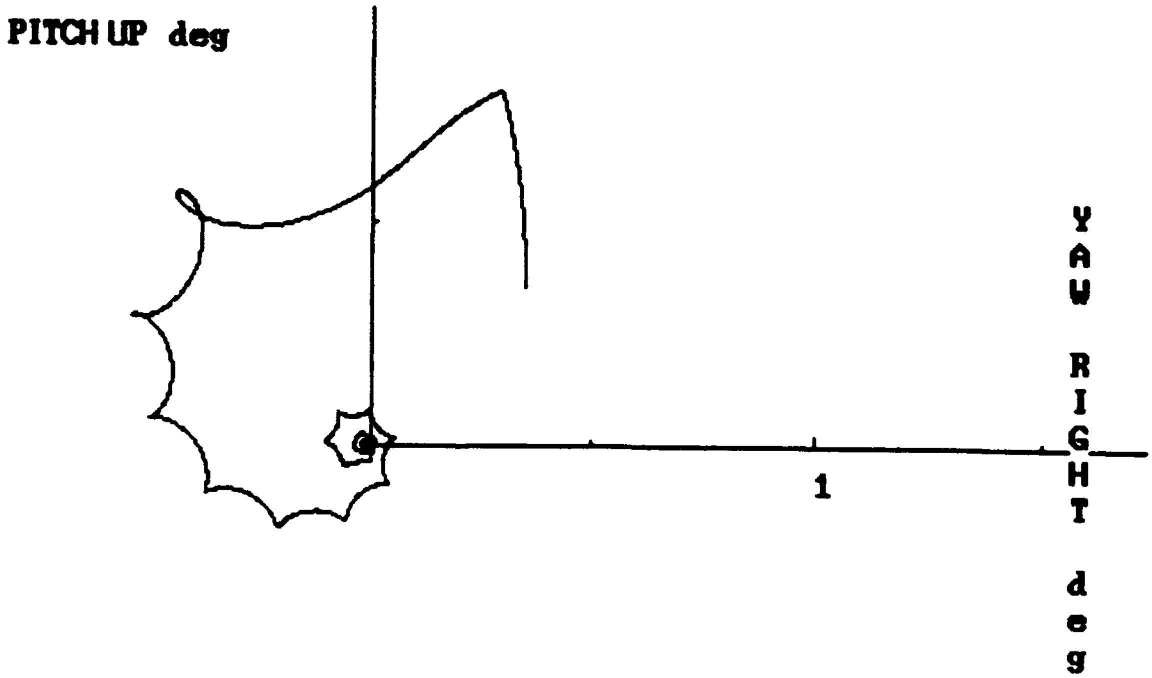

Figure 20. Epicycle Motion of Fin-Stabilized Projectile With High Spin Rate

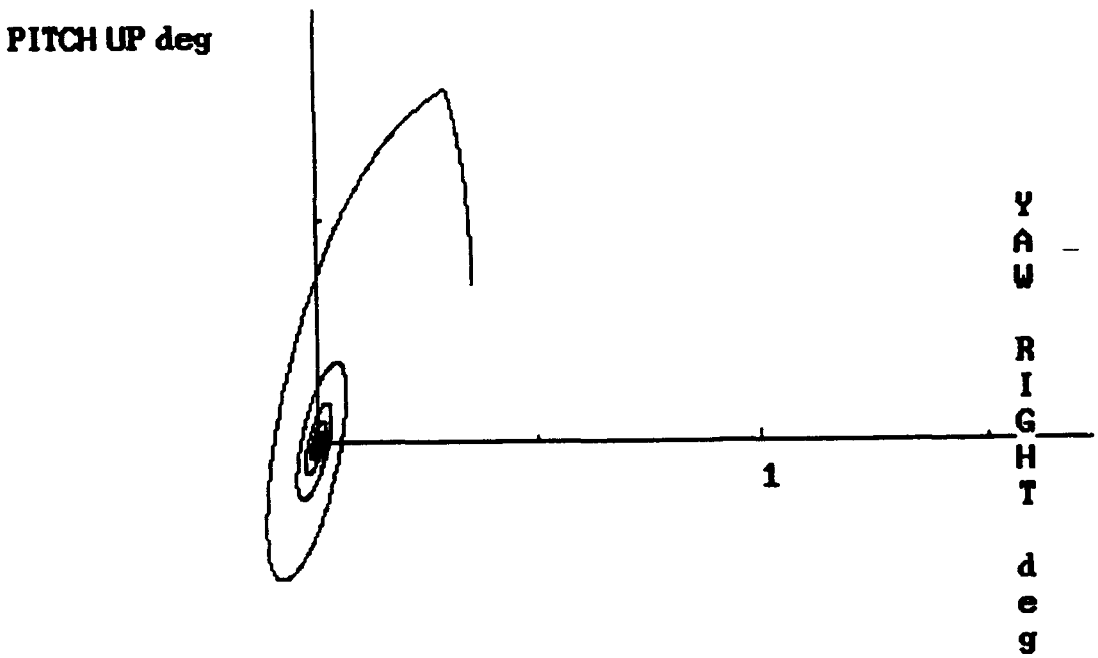

Figure 21. Epicycle Motion of Spin-Stabilized Projectile With Low Spin Rate

foot range, an additional improvement. The rocket thrust was further decreased to 66.67 pounds for a burn time of 1.5 seconds, resulting in a lateral drift of only 0.3 foot at 1,410-foot range. Clearly, reducing the thrust during the first large yaw cycle is having a positive effect on reducing lateral drift. Using these last thrust parameters, the 0.5-degree muzzle jump condition was then shifted 180 degrees in the opposite direction to evaluate dispersion sensitivity. The drift increased in the opposite direction by 0.7 foot to represent a dispersion angle of 0.25 mil, which is outstanding by any measure.

A baseline trajectory to a range of 1,500 feet was then established. Using rocket motor parameters of 66.67 pounds of thrust for 1.5 seconds, with a burn start of 0.04 second results in a time of flight to 1,500 feet of 2.1 seconds. The projectile is launched at a super-elevation of 5.25 degrees with a muzzle velocity of 140 fps. The apogee of the trajectory is about 14 feet. The maximum boost velocity achieved is about 1,050 fps. For this trajectory analysis, the fin cant angle was increased to 0.5 degree from 0.1 degree, since such a small cant angle seemed unrealistic from a manufacturing point of view. Table 11 summarizes the baseline trajectory parameters for a 1,500-foot trajectory.

Table 11. Trajectory Parameters to 1,500-Foot Range for 90mm Fin-Stabilized Projectile

Super Elevation (deg)	Time of Flight (sec)	Apogee (ft)	Max Velocity (fps)	Impact (ft)	Drift Due to Spin (ft)
5.25	2.1	14	1050	+2.24	0.541

I. DISPERSION SENSITIVITY ANALYSIS FOR FIN-STABILIZED DESIGNS

Taking the baseline trajectory, a multitude of system parameters are varied to a small extent to see the resulting change in impact point. In this analysis, a vertical target was chosen at 1,500 feet. Table 12 shows the dispersion parameters and the resulting change in impact-point deflection and height. All results are based on the 6-degree-of-freedom trajectory analysis.

These cumulative dispersion errors are by no means trivial when trying to hit a point target. A typical point target, such as an armored vehicle or bunker, may be described as a vertical target of dimensions 2 meters by 2 meters, or more conveniently a circle of radius 4 feet. At 1,500 feet, this target represents an angular dispersion of 2.7 mils. To hit this target more than 50 percent of the time, one would expect the combined circular dispersion errors for the projectile to be less than 2.7 mils. If the height and drift dispersions are unequal, as in this case, calculating hit probability is more complicated.

Table 12. Vertical Target Sensitivity for 90-mm Fin-Stabilized Projectile

Target Range 1,500 feet

Super-Elevation (deg)	Delta Z (Height) absolute values (ft/mils)	Delta Y (Drift) absolute values (ft/mils)	Comments
5.25	0	0	baseline
5.3025	1.375/0.917	0.000/0.000	1% launch angle error (wanted 5.25 deg, got 5.3025 deg)
5.25	0.926/0.617	0.004/0.003	1% thrust error (67.333 lb for 1.485 sec)
5.25	0.444/0.296	0.009/0.006	1% range aiming error (target really at 1,485 ft)
5.25	1.253/0.835	0.004/0.003	10% motor start time error (started at 0.036 sec)
5.25	0.944/0.629	0.000/0.000	1% projectile weight error (2.8185 lb, not 2.847 lb)
5.25	6.108/4.07	0.014/0.009	10-fps tail wind (6.8 mph)
5.25	0.586/0.391	0.002/0.001	1-fps tail wind (0.68 mph)
5.25	0.431/0.287	81.8/54.5	10-fps cross wind (6.8 mph)
5.25	0.015/0.010	8.18/5.45	1-fps cross wind (0.68 mph)
5.25	0.296/0.197	0.005/0.003	10°F air temperature (69°F instead of 59°F)
5.25	1.111/0.741	0.016/0.011	40°F air temperature (99°F instead of 59°F)
5.25	0.993/0.662	0.005/0.003	1% motor impulse error (101 lb-sec, not 100 lb-sec)
5.25	0.000/0.000	1.37/0.913	1% deflection aim error based on QE (0.0525 deg)
5.25	0.000/0.000	0.054/0.036	10% fin cant angle error (0.55 deg, not 0.50 deg)
5.25	0.423/0.282	0.408/0.272	0.5-deg muzzle jump yaw in third quadrant
5.25	0.425/0.283	0.408/0.272	0.5-deg muzzle jump yaw in first quadrant
5.25	0.583/0.389	0.002/0.001	1% error in muzzle velocity (141.4 fps, not 140 fps)
Cumulative Errors Without Wind Effects (includes 10°F temperature effects)			
		Height	Drift
	feet	7.24	1.87
	mils	4.82	1.24

Using the above cumulative height and drift dispersions as the expected values, the following explains how one can calculate the probability of hitting the target at 1,500 feet. If $\pm$7.24-foot height dispersion represents the range of values in which 50 percent of the errors fall, then zero foot error to 7.24-foot error represents approximately 0.68 standard deviation based on the area under the normal density function. One standard deviation of height dispersion, therefore, equals 10.65 feet (7.24/0.68). For lateral drift dispersion, one

standard deviation equals approximately 2.75 feet using the same formula. A 2 x 2 meter target, 1 meter to the left and right and 1 meter up and down from the aim point, represents approximately 1.2 standard deviations of drift dispersion to the left and right and 0.31 standard deviation of height dispersion up and down. The probability of the shot landing within 1.2 standard deviations to the left and right is 0.77 based on the normal curve if the aim point was the center of the target. The probability of the shot landing within 0.31 standard deviation up and down is 0.24, again based on the area under the normal distribution function if the aim point was the center of the target. The cumulative probability of hitting the target then becomes 0.77*0.24, or 0.18. In other words, 18 percent of the time the round will hit within the vertical 2 x 2 meter target surface.

One could argue that the above dispersion sensitivities represent the extreme conditions, or three standard deviations from the mean, as opposed to the expected values of dispersion. In that case, the standard deviation in drift dispersion becomes 0.623 foot (1.87/3), and the standard deviation in height dispersion becomes 2.42 feet (7.24/3). The 2 x 2 meter target then represents 3.28 standard deviations in drift by 1.36 standard deviations in height. The resulting cumulative hit probability then becomes 0.999 by 0.826, or 0.825—82.5-percent chance of a hit.

In any event, it is this author's opinion that the practical range limit for an unguided projectile of this type will be no more than 1,500 feet. Achieving only 1-percent error in the above-listed dispersion parameters is very good, even for a precision-manufactured projectile and launcher, if there is no fire control support provided to the gunner. Therefore, the above dispersions are closer to the expected values than the extremes. Simple optical sighting mechanisms or stadia line sights will not allow accurate enough range determination or allow tight control of the weapon super-elevation at launch. A laser rangefinder will be required to eliminate any launch angle errors, and the sighting mechanisms will have to inform the gunner of any errors he is introducing in launch angle and deflection angle prior to launch. The gunner will also have to be informed of necessary launch angle corrections to be made in hot and cold weather conditions. Temperature conditions will also affect to a large extent the thrust history of the boost rocket motor. Motors generally burn longer and with less thrust in cold weather and faster and with greater thrust in hot weather, even if the total impulse remains very stable over wide temperature ranges. These thrust profile conditions are an inherent part of solid rocket motors. The gunner will have to compensate in launch angle for these temperature-induced thrust errors. Ignition time of the rocket motor is also a critical dispersion parameter, since the motor starts after launch. Incorporating an ignition system precise to 0.004 second will be a challenge.

J. ANALYSIS OF CROSS-WIND SENSITIVITIES

The cross-wind sensitivity of the projectile, as shown in Table 12, is a substantial problem facing the system developers, for 82-foot lateral drift on a 1,500-foot range with a 10-fps cross-wind is unacceptable. Without the ability to compensate in aimpoint in cases where there is as little as a 1-fps wind (8.2-foot drift) makes hitting the target improbable. With a 10-fps cross-wind (a moderate breeze), hitting the target is an impossibility. Even with aimpoint adjustment to account for cross-wind, aiming 82 feet to the left or right of the target seems very awkward.

More detailed analysis of the cross-wind effect was performed to gain a greater understanding of the problem. Figure 22 shows the epicycle motion of the baseline trajectory with no wind, no initial yaw, and a perfect thrust profile. Figure 23 shows the resulting motion about the flight path with a 10-fps crosswind coming from right to left in the figure. One sees that the cross-wind forces the projectile to nose into the wind, and at the low launch speed this effect is enhanced, most notably during the first yaw cycle. The projectile drift is then aggravated during this first yaw cycle (during rocket boost), since the projectile axis and thrust are pointing to the right. The constant wind condition also does not allow the drift to balance back to the left by forcing the projectile axis into a permanent bias in flight attitude, even as the yawing motion dampens out.

Spin was added to the projectile to see if gyroscopic moments could force the projectile nose back over to the left to balance the thrust-induced drift due to a 10-fps cross-wind. Figure 24 shows the resulting motion with a muzzle spin rate of 100 rad/second, representing one turn in 30 calibers. The resulting drift reduction was 15.5 feet. The muzzle spin rate was then increased to 150 rad/sec and the motor also applied a torque of 1 ft-lb during boost. Figure 25 shows the resulting motion; the drift due to cross-wind for this case was reduced to 43 feet, or nearly half of the baseline case. Nevertheless, more improvement will be required for practical application.

Addition of spin to the projectile may prove, however, to be a problem when there is very little or no cross-wind. Earlier analysis showed that the spinning projectile had inherently more drift than the nonspinning projectile without the presence of cross-wind. On the other hand, drift due to spin is perhaps a more predictable effect than drift due to cross-wind.

The cross-wind trajectory simulation was also run for the nose configuration with the largest yaw oscillation wavelength (nose 1), since this is reported to reduce cross-wind sensitivity. The results were that the cross-wind drift dropped from 82 feet in the baseline case to 70 feet with the alternate nose configuration. This represents a start, but more work will be required to solve this problem in projectile performance.

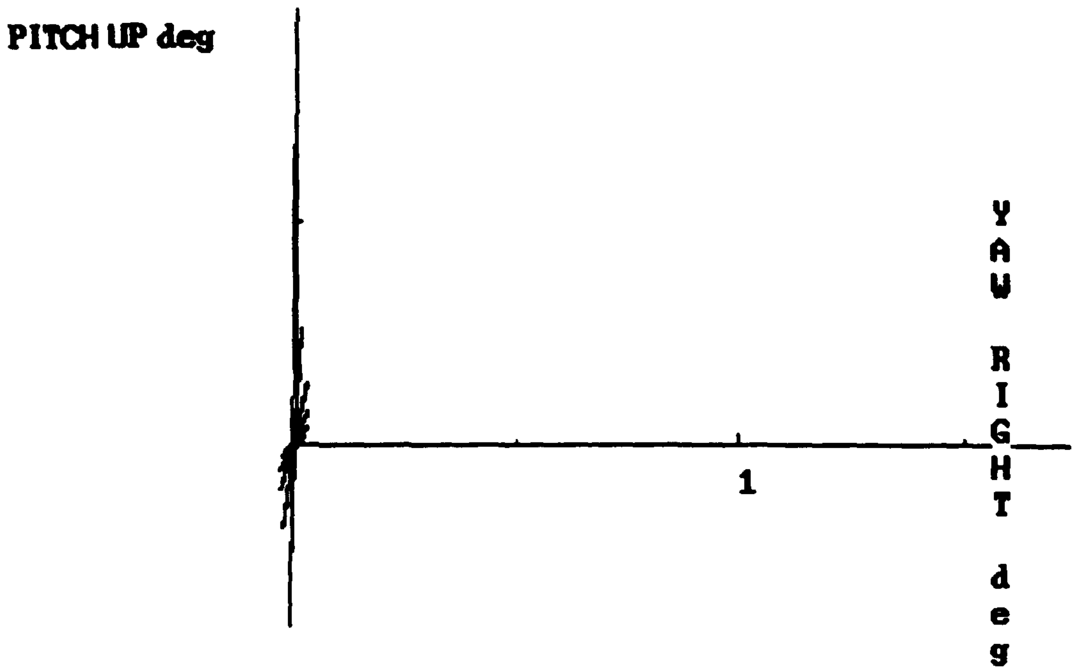

Figure 22. Epicycle Motion of Spin-Stabilized Projectile With Little or No Spin Rate (Baseline Trajectory)

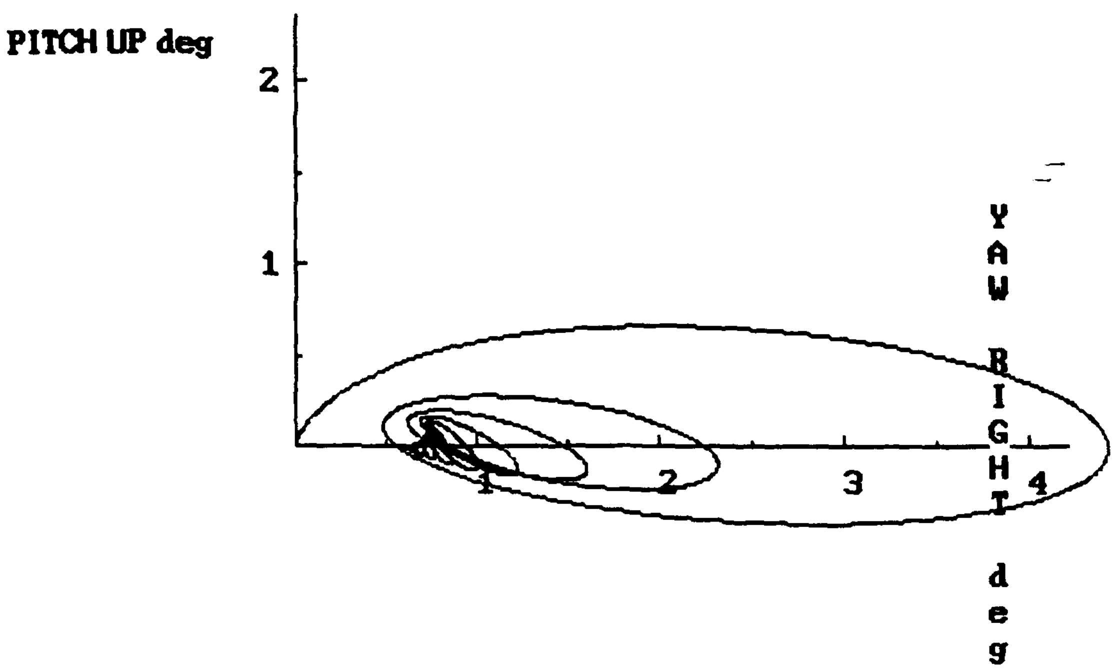

Figure 23. Effect of 10-fps Cross-Wind on Baseline Epicycle Motion

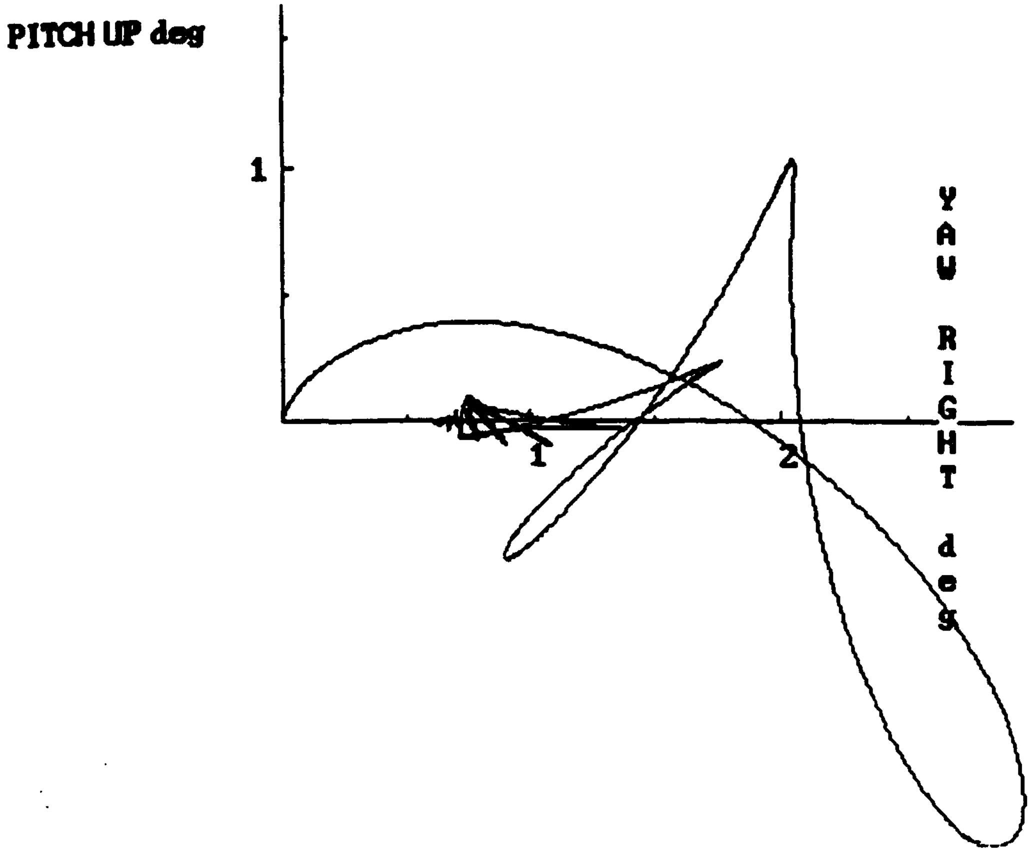

Figure 24. Epicycle Motion With Cross-Wind and Projectile Spin

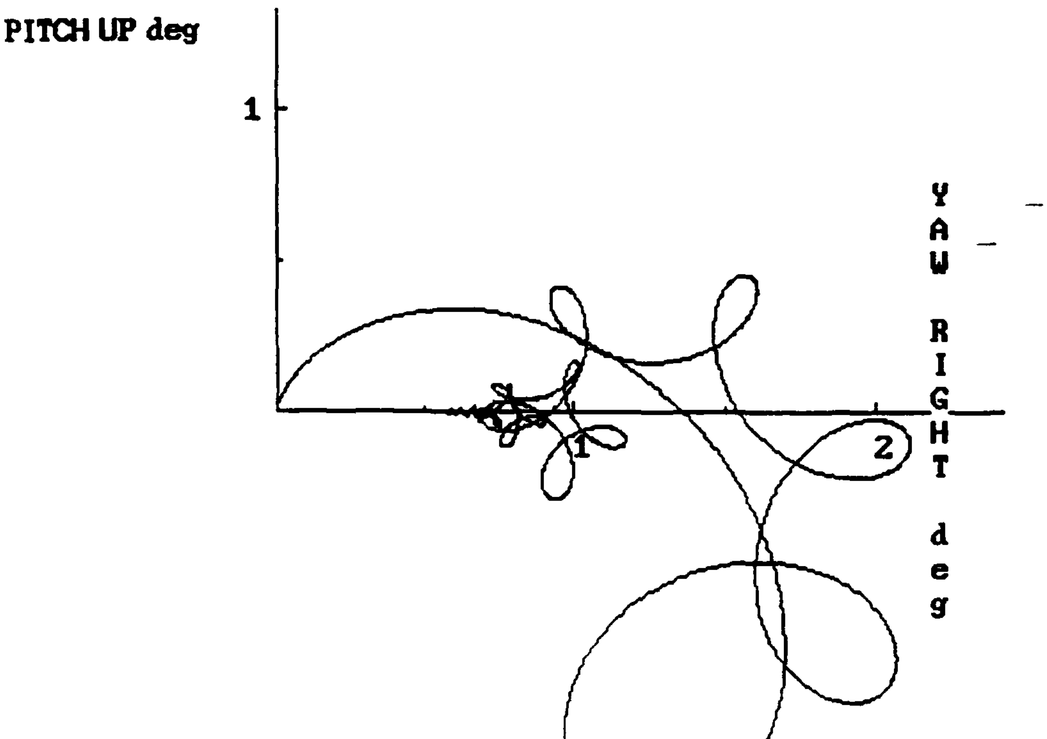

Figure 25. Epicycle Motion With Cross-Wind and Greater Projectile Spin

To illustrate just how susceptible low launch velocity is to cross-wind sensitivity, the baseline fin-stabilized design was fired with a muzzle velocity of 1,000 fps with no external boost motor thrust. With a 10-fps cross-wind, the resulting drift from a perfect trajectory without cross-wind was only 4.6 feet at 1,500-foot range. Ironically, both the external boost trajectory and the full muzzle velocity trajectory had nearly the same time of flight to 1,500-foot range—2.10 seconds with the rocket motor and 1.95 seconds without. This is because the boosted trajectory was speeding up during the first part of the flight for about the same amount of time the unboosted trajectory was slowing down during the later part of the flight. Therefore, cross-wind exposure time is not the issue. The problem is cross-wind during rocket boost.

4. ASSESSMENT OF THE UTILITY OF A GUIDANCE AND CONTROL MECHANISM

The issue of determining whether the incorporation of guidance and control schemes into the weapon system will have value is not one of determining if guidance will increase accuracy, but rather whether one ought to proceed along those lines in the first place. There is no doubt that the technology exists or will exist in the near future to provide a lightweight, reduced-volume guidance and control package for a projectile launcher system such as the one offered by TAC-WEAP. The generic projectile designs presented here weigh less than 3 pounds with a length of less than 17 inches. A weight growth to 5 pounds or more to incorporate guidance and control mechanisms is realistic, and the projectile body can be easily expanded along its length to accommodate these components. Guidance would also allow further reduction in launch velocity to keep recoil levels within safe tolerances. Current command guidance concepts, such a those used in the TOW and HELLFIRE missile systems, make target hit a virtual certainty. Fire-and-forget guidance systems employing millimeter-wave radar or infrared sensors are also under development for projectiles fired from tank guns and mortars or for submunitions dispensed from artillery or aircraft ordnance. In light of this, the community certainly believes that guidance can be applied to just about any projectile for just about any application; it certainly could be examined in this case as well.

The question, however, that needs to be answered is, Why should guidance be employed at all? Within the framework of cost and operational effectiveness, the utility and affordability relationships between guided and unguided systems are very complicated. Adding guidance to the projectile designs considered here will suddenly make a $200 weapon system cost at least $15K to $30K a shot, if not more, not including research and production development expenses. The TOW missile, nearly 30 years after initial procurement, costs about $16,000 a copy. HELLFIRE and COPPERHEAD, 15 years later cost about $20,000 each. Developmental systems such as FOG-M and JAVELIN are estimated to weigh in at no less than $50,000 a copy—some would argue up to $80,000 a copy. Who really knows how high it can go? Under these circumstances, a guided weapon must be many things to many users; unfortunately, in the end, it may be shelved for not meeting unreasonably high expectations.

An inexpensive, albeit less versatile system, on the other hand, may ultimately make it into the hands of the user because it is affordable. The technology exists to produce the unguided projectiles described in this report, along with their launchers, for about $200 each.

Against a point target, such projectiles may only have an unguided effective range of 750 to 1,500 feet. Nevertheless, it may have one unique aspect—meet the requirements of soldiers in the field for some of the toughest combat missions. Furthermore, one slightly limited system in the field, available when it is needed, is worth more than all the sophisticated hardware in the world sitting on the shelf back home.

This is not to say that the performance of the unguided projectiles presented here cannot be improved. This analysis was performed in a manner of a few weeks. Problems with the system will naturally emerge right away; solving these will take more time, imagination, and patience.

The TAC-WEAP system is also no more or less limited in its point-target effective range than other shoulder-fired rocket systems employed today. A survey of the actual performance of these types of systems will show that they are accurate to no more than 1,000 feet. To overcome these shortfalls, advances in electronics miniaturization have led to the development of control systems for projectiles that are not command or terminally guided in nature. In other words, miniature on-board sensors, such as gyroscopes and accelerometers, allow control systems to correct the flight attitude of missiles to improve their stability and make them better follow the intended flight path to either a stationary or moving point target. Systems under development to incorporate these concepts include the advanced 2.75-inch rocket and the SRAW (Short-Range Antitank Weapon) missile system. SRAW employs what is basically a miniaturized inertial guidance system with jet reaction control thrusters to give the missile at least a 0.70 hit probability out to 500 meters (1,640 feet). Projected unit production cost is $3,800 per missile. This system has been built and tested, and therefore represents available technology. The 2.75-inch rocket employs a less sophisticated and much less costly form of stability enhancement to reduce dispersion. The improvements in accuracy are appreciable and represent additional, readily available technology.

Advances in miniaturized optics, such as those found in cameras and heads-up displays in aircraft, make incorporating advanced fire control into a shoulder-fired weapon a near-term possibility. A combination telescopic sight with a laser rangefinder) and temperature and wind sensors, coupled to a simplified on-line ballistic range table, may make accurate firing as easy as placing the sight on the target and pushing a button for an aimpoint correction. Investing in the development of this technology, of course, would benefit all shoulder-fired weapons.

5. PROPOSED TAC-WEAP SYSTEM POTENTIAL

Over the course of history, innumerable scientific and engineering ideas that were initially deemed ludicrous and impossible by the wise men of the time ultimately proved to be great revolutionary developments of the future. Examples of this include heavier than air flying machines, the helicopter, space travel, the submarine, and supersonic aircraft, to name just a few. In the field of ballistics and conventional weapons, the same is true. Otherwise, why are thousands of us still working in this field hundreds of years after the invention of gun powder? The lesson is that the future belongs to those who dare to push the limits of conventional wisdom.

The staff of TAC-WEAP Ventures, Inc., through their vision and experimentation, have without doubt expanded the envelope of capabilities for shoulder-fired ordnance with the invention of their closed-breech concept. This study has provided scientific insights into how projectiles such as those used in the TAC-WEAP system (i.e., of significant weight and therefore, lethality) can be safely and effectively fired from a closed-breech, shoulder-fired weapon system. There is no need in this report to further refine the specific projectiles for this application in order to prove their viability, since the launch and flight environment is rather benign from an engineering point of view. The high-low pressure interior ballistics concept (i.e., generation of peak pressures no more than a few hundred pounds per square inch), is well understood. The projectile accelerations are on the order of only several thousand times that of gravity, and the rocket motor requirements are rudimentary. The body of knowledge exists to develop safe and effective projectiles in these calibers and weights for much more demanding requirements. What is still needed is to fully develop the potential of the weapon system concept.

It is a conservative position to state that warhead calibers from 90mm to 125mm will have acceptable lethality against modern light to medium threats. It is certainly feasible to incorporate existing warhead technology into a projectile for this weapon system, and the lethality outcome can be anticipated without actually fabricating and testing the warhead at this point in time. There is no reason to expect that a projectile designed for this system will not have acceptable lethality for its caliber. It is an engineering development task that simply has to be performed.

The challenge remains, as always for unguided projectiles, to develop systems of high accuracy. In this respect, based on the analysis performed here, the expertise of the analyst, and the tools employed in the analysis, this system appears to have perhaps no more and

no less unguided accuracy than equivalent systems in existence today—an effective range on a point target of about 300 meters. Since TAC-WEAP has never demonstrated the viability of the second-stage boost rocket motor, this issue can always be debated. This researcher is of the opinion, however, that the advantages of this system outweigh the potential disadvantages. Performing the second-stage demonstration with more in-depth projectile design is worth the investment and risk.

The clear advantages to this system are several. First, it employs a closed-breech launch mechanism, resulting in no back-blast danger area. This makes it a true urban-area fighting weapon with great potential for reduced launch signature and subsequently improved gunner survivability in close-in, built-up area combat. Secondly, its shoulder-fired, rifle-type design makes it a natural system for a soldier to employ. In combat, often victory goes to the one who fires first. A rifle-type weapon is a system that can be employed instinctively, fired from the hip if necessary, and brought to the shoulder and fired without conscious aiming if required. Such quick reaction often makes the difference between living and dying in battle. Finally, a rifle-type weapon is an offensive weapon. It has inherent mobility in the way it is grasped and held—ready to be employed immediately. A gunner can stalk his target without concern for giving away his position once ready to fire, without endangering those around him when he does fire, and without drawing attention to himself after firing.

There is no reason for any segment of the armed services to not consider investing in the development of this weapon system concept. In defense procurement, where a system's worth is ultimately proved on the battlefield, and dollars and cents are counted in lives, no one should consider investing in new ideas, such as this one, as a threat to technology currently under development or consideration. This system has clear advantages if successful; its potential limitation will present technical challenges to overcome prior to becoming operational. However, the system appears feasible, and it certainly has utility. Based upon the analysis presented here, it is recommended that the government seriously consider a measured amount of funding to further develop the TAC-WEAP system.

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Appendix

RECOIL IN SHOULDER-FIRED WEAPONS: A REVIEW OF THE LITERATURE

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LETTER REPORT

NUMBER 296

RECOIL IN SHOULDER FIRED WEAPONS: A REVIEW OF THE LITERATURE

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February 1982

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Dover, NJ

US ARMY HUMAN ENGINEERING LABORATORY

RECOIL IN SHOULDER FIRED WEAPONS: A REVIEW OF THE LITERATURE

At the request of the Joint Service Small Arms Program, Fire Control and Small Caliber Weapon System Laboratory (FC&SCWSL), Light Weapons Development Team, the US Army Human Engineering Laboratory Detachment-ARRADCOM conducted a limited literature search on the effects of recoil and design considerations to reduce the actual and perceived recoil of shoulder fired weapons. This paper summarizes the findings of the literature search.

Two components of recoil are impulse and energy. These two combine to give the sensation commonly known as "kick". The recoil force strikes the shooter in a series of waves. These shocks are not felt as separate entities. The shooter gets the full effect after the projectile has left the muzzle and the rapidly expanding gases strike the atmosphere. This is a violent contact and reacts on the weapon and shooter very abruptly.

While energy and impulse are two of the major components of recoil, there are several other factors which contribute to the effect on the shooter. These other factors are as important as the energy and velocity components associated with firing weapons and must be considered early in the design of weapons.

An analysis of shoulder-fired weapon firing situations reveal that when a weapon is fired a reactive force is directed backward toward the shooter's shoulder and body. This force is governed by Newton's Third Law of Motion and is a function of the effective mass and imparted velocities of the weapon, the temporal and spatial distribution of the impact forces, the velocities and masses of the projectile, powder charge, expanding gases and the presence or absence of flash hiders, muzzle brakes, etc. (1)

Typical recoil energies of several standard weapons are calculated as follows:

a. Recoil energy of Caliber .30 M1 Rifle:

Projectile impulse = Projectile mass x velocity/g_c = 2.3 lb-sec.

Rifle impulse = $mV/g = 9 \times 8.25/32.2 = 2.3$ lb-sec.

Recoil velocity = $V = Ig/m = 2.3 \times 32.2/9 = 8.25$ ft-sec.

Recoil energy = $E = mV^2/2g = 9 \times 68/64.4 = 9.5$ ft-lb.

b. Grenade Launcher, M79:

Projectile impulse = $.375 \times 240/32.2 = 2.8$ lb-sec.

Recoil velocity = $2.8 \times 32.2/6.5 = 14$ ft-sec.

Recoil energy = $mV^2/2g = 6.5 \times 194/64.4 = 19.6$ ft-lb. (15)

The physical impact of the weapon on the shooter's shoulder may have tissue damaging qualities that may induce pain, soreness, stiffness, tenderness, etc.

These conditions may result in reducing the tightness with which the shooter holds the weapon and may result in a less steady rifle at the time of firing, hence poorer shooting performance.

As weapon recoil increases via increased powder charge there would be an increase in noise and gun blast. These auditory stimuli are known to produce involuntary startle patterns in the shooter. Data show (1) that as intensity of noise increases the degree of startle also increases. During timed or rapid fire the recovery from such startle movements might reduce measured marksmanship proficiency by causing the shooter to fire hurriedly and without adequate preparation.

Exaggerated startle, induced by high levels of noise and gun blast may affect marksmanship performance by causing the shooter to jerk the trigger when he hears the shot from a rifle next to him.

A combination of intense recoil impact and intense gun blast may increase the probability of anticipatory flinching patterns. Sources [9][10] suggest that this type of flinching is a case of conditioning and its development is favored by (1) poor previous marksmanship training, (2) high subjective anticipation of pain from the firing, and (3) high levels of general anxiety.[11]

Once the affects of recoil and noise on the shooter is understood, it is possible to look at the structural and design characteristics of the weapon which affect perceived recoil.

One major design factor in controlling perceived recoil is the weapon's weight. A light weapon has more kick than a heavy weapon, given the same caliber. A study [2] conducted in 1955 varied the weight of M1 Rifles from 9.81 lbs to 14.25 lbs. The change in weapon weight had the affect of lowering recoil from 12.71 ft-lbs (for the 9.81 lb weapon) to 8.77 ft-lb (for the 14.25 lb weapon).

Another study conducted in 1955[4] varied recoil while maintaining weapon weight. In this study the ammunition was varied to produce differing recoil. The recoil energies of the ammunition ranged from 11.0 ft.-lb. to 25.5 ft.-lb. The result of this study showed that marksmanship performance was constant when recoil was varied from 11.0 to 19.3 ft-lb. As recoil was increased from 19.3 to 25.5 ft-lbs, significant differences in all measures of marksmanship performance were noted.

Similiarly the findings indicate that variation in recoil is associated with differences in resultant tissue damage. A total of seven subjects exhibited some redness and swelling during the experiment, ecchymatic areas (bruises) were exhibited by fifteen subjects. More subjects in the two higher recoil groups (25.5 and 19.3 ft-lbs) developed bruise areas compared to the two lower recoil groups (14.9 and 11.0 ft-lbs). Since a majority of the bruise areas were initially orange-yellow in color and since they did not develop in many subjects until the second or third day of shooting, it can

be inferred that the hemorrhaging was not superficial, but occurred in the deep tissue.

Another major design consideration is the weapon's stock configuration. Stock design should be dictated by the intended aiming technique for the weapon. A stock configured for slow aimed fire would differ from one optimized for quick pointed fire. Aimed fire implies the use of the rifle sight and is the type of fire done on the target range. Pointed fire is considerably different from aimed fire. In this mode the soldier simply points the weapon and fires, not taking time to use the sights. A weapon configured for effective rapid unaimed fire can be readily made to deliver accurate slow aimed fire, but the opposite is not true. This is because such things as a sighting rib or optimum butt stock length are not required for accurate aimed fire but are of vital importance for rapid fire effectiveness.[3]

Not only is stock configuration important for effectively controlling the weapon, it is important in reducing the amount of perceived recoil. There are three basic dimensions that must be determined if a weapon is to point properly and decrease the amount of felt recoil. They are length of pull, drop at heel and comb height.

Length of pull is normally defined as the distance between the center of the trigger and the center of the butt plate. A stock has correct length of pull when it is short enough to be lifted straight up to the shoulder and long enough so that when the shooter places his head on the stock, recoil won't cause him to jam his thumb into his nose or cheek.[5] For military weapons which must accommodate a large range of body sizes the optimum length of pull is 13.5 ± .5".

Drop at the heel and the slope of the comb are the determining factors in placement of the gunner's eye behind the barrel. The shooter's eye should be 3 ± .5" behind the rear aperature for peep sights and 12 ± 2" behind the rear sight for notch type designs.[3][5] Drop at the heel should not exceed 2.5" with a 3 degree maximum slope.[3][5]

The amount of drop at the heel is important in reducing the perceived recoil. Older weapons were commonly stocked with a lot of drop which increased perceived recoil. In general, the straighter the stock (minimum of drop) the less perceptible the kick.[6] The Monte Carlo stock raises the shooter's cheek and eye above the normal position and drops off as it approaches the butt plate. This places the butt of the weapon below the comb line and the cheek in line with the bore axis, all of which help to reduce perceived recoil.

The butt plate of the stock is also important in determining perceived recoil. If it is too short vertically and too narrow horizonally the perceived recoil will be more harsh than if it had been properly dimensioned. The larger the butt area the larger the area of contact to the shoulder. This will reduce the recoil energy (ft-lbs) as the energy is applied over a larger surface area. The optimum dimensions of the butt area should be not less than 5½" in height and not less than 1½ in width.[6]

A ventilated recoil pad will also reduce the effects of recoil by providing a softer area of contact for the shooter's shoulder. In addition, the rubber pad will cling to the shoulder, reducing the tendency for the weapon to slip on the shoulder. Some sources have placed a figure of a 10% reduction in perceptible recoil by the addition of a ventilated recoil pad. (6)

The pistol grip is another important factor in helping to reduce and control recoil. A straight grip does not provide the shooter enough surface area to properly hold the weapon against the rearward forces generated during weapon firing.(6) Some weapons have a pistol grip which is a continuous curve from the rear of the trigger guard to the bottom of the grip. This may allow the shooter's hand to slide around past the curve. The pistol grip should have a stop at the bottom for the little finger of the trigger hand. This will help maintain control of the weapon and prevent the hand from slipping off. (5)

The weapon's forestock is another major consideration in reducing perceived recoil. The forestock should be wide enough and highly textured to provide a good gripping surface to facilitate pulling the weapon tightly into the shoulder. Other factors, such as insulating the shooter from barrel heat dictate the actual dimensioning.

A sling may also assist in controlling a weapon and reducing perceived recoil by permitting the shooter to grip the weapon more tightly to the shoulder.

Accessories such as flash hiders and muzzle brakes are known to affect recoil directly via their effect on the escaping gases and as sources of additional weight. (1) However, muzzle devices that compensate for muzzle climb are of questionable value for most combat rifles as they must be tuned to each particular shooter and firing position. Muzzle brakes that reduce recoil become more effective as the ratio of projectile weight to propellant weight approach 1:1.(3)

One additional design consideration for reducing perceived recoil was investigated during a test which compared aiming error, time to fire, force-time estimates and subjective estimates of three pairs of identical weapons. One of the weapons of each pair was equipped with a Hydro-coil soft recoil device. In the subjective estimates, the Hydro-coil equipped weapon was judged to have less kick than a non Hydro-coil equipped weapon 77% of the time. (8)

In addition to the previously cited studies regarding accuracy versus recoil(2) (4) the following tables and graphs are provided as references. Table 1 and Chart 1 show the recoil of some popular hunting cartridges and the REDEYE Missile. Chart 2 can be used for computing recoil energy or recoil impulse given weapon weight.

TABLE 1 (6)

RECOIL OF POPULAR HUNTING CARTRIDGES

Cartridge	CARTRIDGE Muzzle Velocity (f.p.s.)	CARTRIDGE Bullet Weight (grs.)	CARTRIDGE Powder Charge (grs.)	RIFLE Mass (lbs)	RIFLE Recoil Velocity (f.p.s.)	RIFLE Recoil Energy (ft-lbs)
.22 L.R.,H.V.	1365	40	3	5	1.76	.24
.22 Hornet	2690	45	10	6 3/4	3.56	1.33
.220 Swift	4100	48	39	8	8.52	9.02
.222 Rem	3200	50	21	7	5.66	3.48
.222 Rem Mag.	3300	55	23	7	6.41	4.57
.243 Win.	3070	100	38	6 1/2	11.23	12.72
6mm Rem.	3200	90	41	7	10.56	12.12
.250 Savage	3030	87	38	7 1/2	8.86	9.14
.257 Roberts	2650	117	36	8	8.52	9.02
.270 Win.	3140	130	45	8	11.66	16.88
7mm Rem. Exp.	2810	150	48	7	13.42	19.58
.30-30 Win.	2220	170	30	6 1/2	10.85	11.88
.30-'06	2700	180	48	8	12.73	20.13
.300 Savage	2370	180	34	7 1/2	10.81	13.60
.300 H&H Mag.	2920	180	58	8	14.60	26.77
.300 Wby. Mag.	3060	180	80	8 1/4	16.95	36.83
.308 Win.	2610	180	45	6 1/2	14.84	22.22
.338 Win.	2700	250	70	8 1/2	16.9	37.69
.35 Rem.	2210	200	39	7 1/2	11.29	14.85
.358 Win.	2250	250	52	8	13.7	23.71
.375 H&H Mag.	2740	270	69	8 1/2	19.11	45.3
.458 Win.	2125	510	69	9 1/2	20.16	60.00
.460 Wby. Mag.	2600	500	120	10 1/2	25.11	102.84

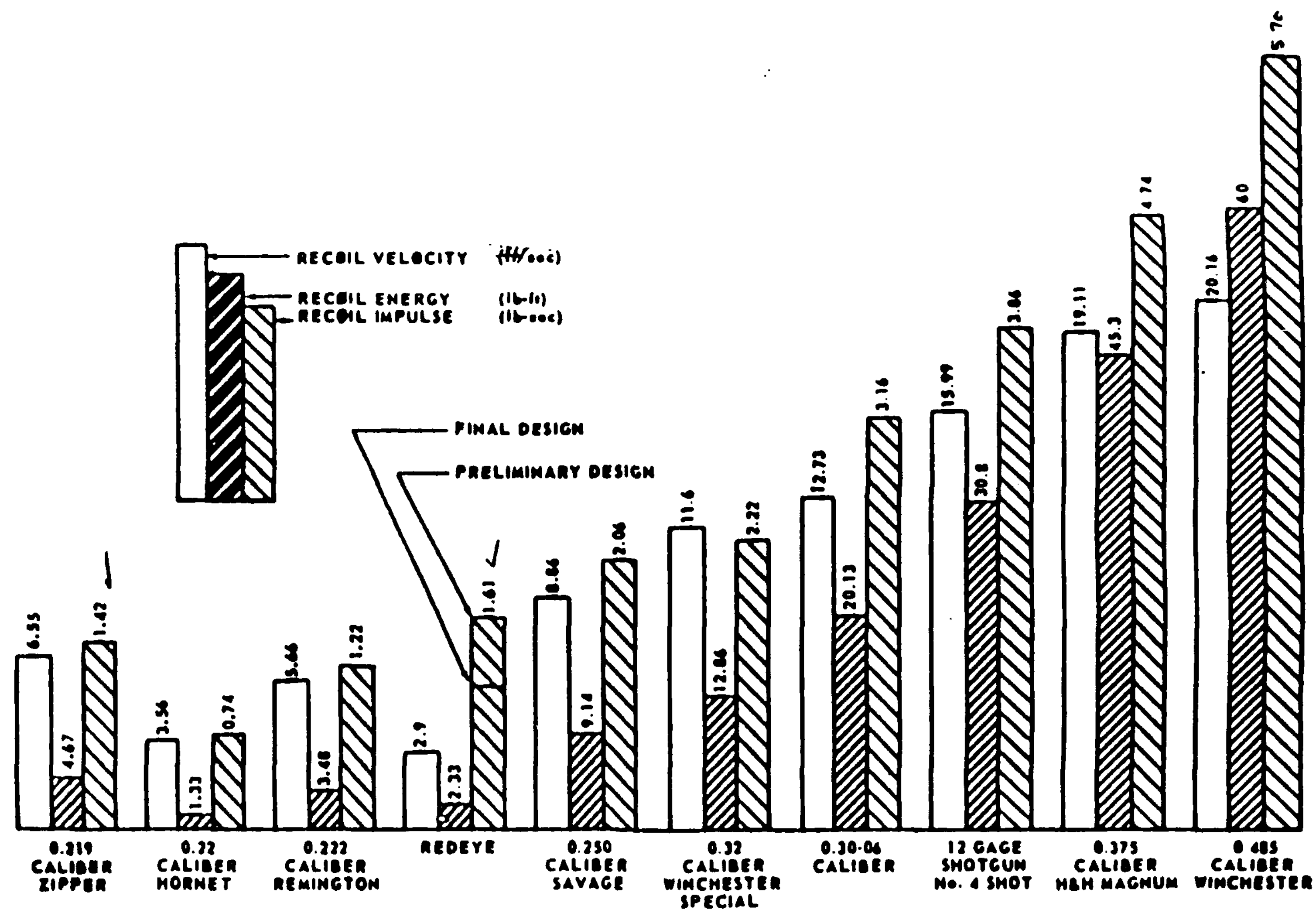
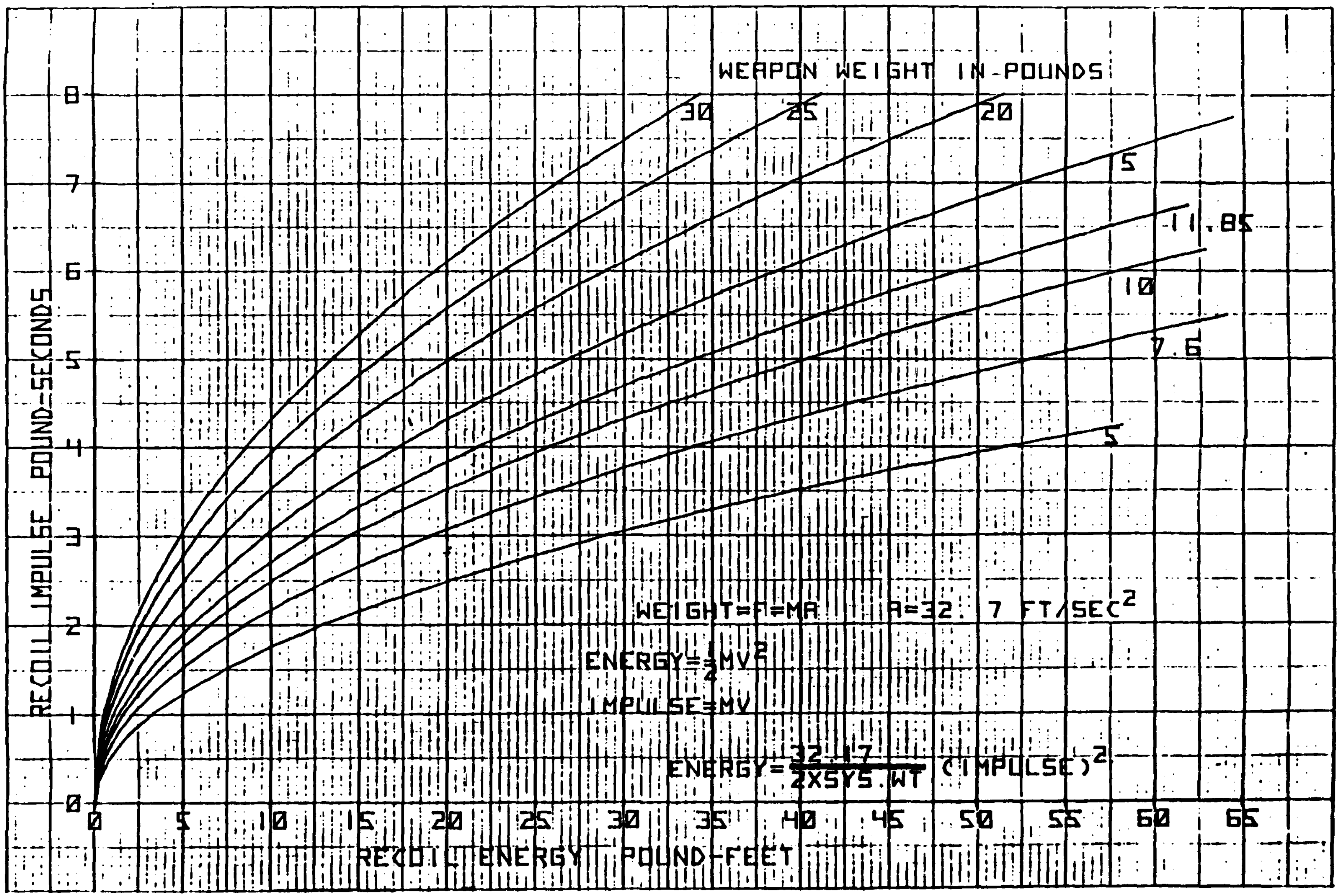


CHART 1 - RECOIL COMPARISON OF VARIOUS WEAPONS (16)

CHART 2 (16)



WEAPON WEIGHT IN-POUNDS
30
25
20
5
11.85
10
7.6
5
WEIGHT=F=MA
A=32.7 FT/SEC²
ENERGY=½MV²
IMPULSE=MV
ENERGY=32.17/2X5Y5.WT (IMPULSE)²
RECOIL IMPULSE POUND-SECONDS
RECOIL ENERGY POUND-FEET
0
1
2
3
4
5
6
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8
0
5
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15
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65

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